1. Computer Prehistory – Calculating Machines

"*For it is unworthy of excellent men to lose hours like slaves in the labour of calculation which could safely be regulated to anyone else if machines were used*", Gottfried Wilhelm Leibniz, 1685.

The Origins of the Computer

For centuries, scholars have striven to develop tools to simplify complex calculations. As demand increased and the technology advanced, these became increasingly sophisticated, eventually evolving into the machines that are the direct ancestors of modern computers. Therefore, the origins of the electronic digital computer lie not in the electronic age but with the development of mechanical calculating aids and mathematical instruments. In order to fully understand the amazing developments that took place in the 20th century, it is necessary to go further back in time and examine humanity's earliest efforts to mechanise calculation.

Calculating Aids

The need for tools to aid the process of mental calculation first arose with the adoption of trading by ancient civilisations and the subsequent development of numerical and monetary systems. In the absence of written numerals, and as trading became more widespread and the arithmetic calculations increasingly complex, merchants began using readily available objects such as beads or pebbles to help keep count. These evolved into the earliest calculating aids.

The first calculating aid was probably the counting board, a flat rectangular board made from wood or stone and marked with parallel lines to provide placeholders for the counters. Each line denoted a different amount, such as tens, hundreds, thousands and so on, and numbers were represented by the combined positions of a set of counters on the board.

Many ancient civilisations also employed the abacus as a calculating aid. An abacus is essentially a more convenient form of counting board in which the counters are held in slots or threaded on wires to keep them in place. Numbers are represented by moving the appropriate counters in each line from one side to the other. Its origins are obscure but the earliest known example is the Sumerian abacus from southern Mesopotamia which dates from around 2500 BC. The simplicity of the abacus belies a powerful capability in the hands of a

trained user and modern versions can still be seen in use in some parts of Asia.

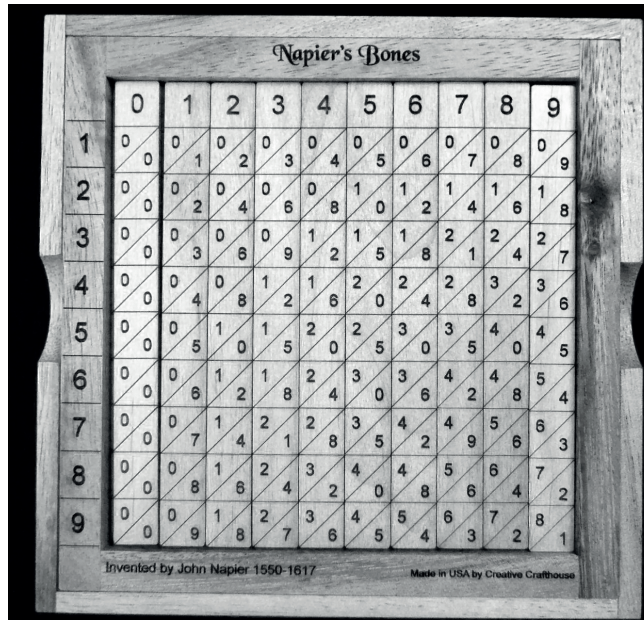
The counting board and abacus were useful aids for addition and subtraction calculations but less so for multiplication and division. Following a reawakening of interest in mathematics amongst European scholars that began in Italy during the Renaissance, mathematicians began to develop more sophisticated aids to calculation. The first person to make a major contribution in this field was the influential Scottish mathematician and theologian John Napier.

Born in Merchiston, Edinburgh in 1550, John Napier came from a wealthy family of Scottish noblemen and his scholarly pursuits were conducted purely as a hobby rather than in any professional capacity. Nevertheless, he made several important contributions to mathematics, not least of which were his calculating aids. Napier's first major achievement in this field was the invention of logarithms in 1614. Logarithms reduce a tricky multiplication or division calculation to a simple addition or subtraction by representing numbers by the power or exponent to which the base must be raised in order to produce the result. Logarithm values were pre-calculated for a range of numbers and distributed in tabular form. However, the production of such tables was a lengthy and exacting task. Automating this work would be a recurring theme in the history of calculating machinery but for now this process would remain a manual one.

In his book 'Rabdologiae', which was published shortly after his death in 1617, Napier describes another invention also aimed at simplifying the process of multiplication. It comprised a set of ten rods of square section inscribed with numbers grouped in pairs corresponding to the digits 0 to 9 inside a square with a diagonal line separating them, plus an additional rod inscribed with a column of the digits 1 to 9 arranged vertically downward which was used to represent the multiplier. To multiply one number by another, the rod representing the multiplier was placed alongside a set of rods in the correct order necessary to represent the multiplicand, thereby creating what was essentially a multiplication table. For single digit multipliers, the product was then read off from the appropriate multiplier row by simply adding the pairs of numbers within each diagonal strip from right to left, performing a tens carry where necessary. For larger multipliers, the partial products were read off in turn and then added together.

By reducing the task of multiplication to a series of simple additions, Napier's invention significantly increased the speed and reliability with which such calculations could be performed. The rods could also be used to help simplify division calculations and later versions included two additional rods for the calculation of square roots. Napier's rods became more commonly known as Napier's Bones due to the frequent choice of ivory or bone as the material for their manufacture. Being easy to use and relatively cheap to make, they became very popular, their use spreading rapidly throughout Europe and even

reaching China through the work of Jesuit missionaries.



Napier's Bones

Napier's earlier invention, logarithms, led to the development of the second important early calculating aid, the slide rule. The first practical slide rule was invented by the English mathematician and clergyman William Oughtred in 1622. Oughtred's device was based on the work of Edmund Gunter, an instrument maker and professor of astronomy at Gresham College, London, who two years earlier had created his 'Line of Numbers', a logarithmic scale in the form of a long wooden bar which was used to multiply numbers together by marking off lengths corresponding to the numbers using a pair of dividers. Oughtred realised that the dividers could be eliminated by adding a second scale placed alongside which could be repositioned relative to the first. Furthermore, if these scales were circular rather than linear, a more compact instrument would result.

Oughtred designed his instrument with two concentric rings made from brass and engraved with a series of circular logarithmic scales. Two arms which pivoted about the centre were also fitted to aid reading. He named it his 'Circles of Proportion'. The basic design of the slide rule was gradually refined over the years until it finally reached its familiar (linear) form in 1850. Although requiring more care to use than Napier's Bones, it was a more versatile instrument and remained a popular calculating aid until superseded by electronic pocket calculators in the 1970s.

John Napier's work is the starting point for our story. Calculating aids such as Napier's Bones and the slide rule were a welcome improvement on manual methods but they were far from automatic. Fortunately, advances in mechanical technology were also taking place throughout this period and these would allow mathematicians to create much more capable devices for calculation, calculating machines.

Building Blocks – Geared Mechanisms

Geared mechanisms, in which toothed wheels operate together to impart some form of precision movement, were first introduced by the ancient Greeks. Gears were originally developed to transmit power for heavy lifting applications but were gradually refined for use in more sophisticated applications such as water-powered clocks and mechanised representations of the heavens. They may also have been employed in mechanical automata, animated figures devised for entertainment or ceremonial purposes.

Descriptions of such devices first appear in the writings of Philon of Byzantium who lived during the 3rd century BC. The celebrated Greek mathematician and scientist Archimedes of Syracuse, who also lived during this period, is known to have contributed greatly to the development of geared mechanisms, although his own writings on the subject have been lost. Hero of Alexandria, a Greek inventor who lived in the 1st century AD, also wrote extensively on the subject. However, despite the written evidence supporting their existence, very little was known about these early mechanisms and no examples were thought to have survived until the discovery of a mysterious object in an ancient shipwreck off the Greek island of Antikythera in 1900.

The Antikythera Mechanism

The Antikythera Mechanism consists of seven main fragments plus seventy or so smaller pieces. It was discovered by sponge divers in the wreckage of a Roman ship that had foundered during the 1st century BC. A large number of archeologically significant artefacts such as bronze and marble statues were also recovered from the shipwreck and the mechanism fragments were initially ignored, their true nature obscured by a covering of petrified debris. However, in May 1902 archaeologists noticed an inscription on one of the fragments, prompting further investigation which revealed them to be pieces of the earliest surviving geared mechanism.

Early investigations of the Antikythera Mechanism were hampered by the calcified condition of the fragments and it was not until the 1970s that advances in x-ray imaging techniques allowed researchers to examine the internal structure in sufficient detail to attempt a reconstruction. These studies showed that the complete mechanism would have contained at least 31 bronze gears in

a wooden-framed case about the size of a shoebox which was fitted with bronze plates on the front and back faces. A large dial dominated the front face of the case and two smaller dials were engraved on the back face. The gears ranged in size from around 9 to 130 millimetres in diameter and feature precision crafted triangular teeth with a pitch of approximately 1.5 millimetres. They were arranged in a complex configuration which included compound gear trains and the first known example of differential gearing, where a large gear is meshed with two smaller gears of different size that rotate at different rates.

The Antikythera Mechanism is likely to have been operated by turning a handle of some description through the desired number of revolutions until a specific date was reached then reading the resulting values from pointers on each dial. However, opinions differ over its intended purpose. The presence of astronomical symbols on the dials and inscriptions referring to the planets Mars and Venus suggest an astronomical or astrological use. The cycles of the sun and moon are accurately represented, rendering the device capable of predicting eclipses but it may also have been designed to model the motions of the five known planets.

The Antikythera Mechanism was a much more sophisticated and higher precision geared mechanism than was previously thought possible in the ancient world, leading to speculation that it was a fake or from a much later period than the other objects from the shipwreck would suggest. However, descriptions of similar devices appear in the writings of the Roman politician and philosopher Marcus Tullius Cicero who lived during the 1st century BC and most experts who have studied the Mechanism now agree that it dates from around 150-100 BC.

Early Astronomical and Calendrical Instruments

The advanced mechanical technology of the Hellenistic period so impressively exemplified by the Antikythera Mechanism is of a level of sophistication not seen again until the Middle Ages. Only one other geared mechanism from antiquity has been found, a portable sundial with associated calendrical gearing from the early Byzantine period which dates from between 400 and 600 AD. However, with only four known gears, this device is much simpler in design and noticeably cruder in construction. The knowledge required to create such mechanisms then seems to have been lost for several centuries, only to re-emerge in the Islamic world at the end of the first millennium.

The great Persian scientist, Al-Bīrūnī, describes a mechanical calendar instrument very similar to the Byzantine device in a book devoted to the construction of various types of astronomical instruments which was written in 996 AD. Al-Bīrūnī's version, which he named 'The Box of the Moon', featured eight brass gearwheels with triangular teeth housed in a circular case. Dials on the front of the case indicated the positions of the sun and moon in

the zodiac and also the phase of the moon for any given day of the month. Unlike the other instruments described in his book, Al-Bīrūnī provides no information on the originator of the calendar, suggesting that such devices were already well known to Islamic scholars, having been handed down from ancient times, and that the Byzantine sundial was perhaps a relatively poor example. The calendar would have been fitted to the back of an astrolabe, an early astronomical instrument used to determine the positions and movements of heavenly bodies.

Mechanical calendars and astrolabes became more closely integrated in later designs, resulting in the instrument known as a geared astrolabe. The earliest known example of such an instrument was constructed by the Persian metalworker Muhammad ibn Abi Bakr al-Isfahani in 1221/22. This used an arrangement of seven brass gears to model the movements of the sun and moon in a similar manner to that described by Al-Bīrūnī. Now in the collections of the Museum of the History of Science at Oxford University, it is the oldest surviving complete geared mechanism.

Geared Astrolabe (Photo © Museum of the History of Science)

As Islamic scientific knowledge began to permeate the West via Islamic Spain and the Crusades, geared astrolabes were soon being constructed in France.

The earliest example dates from around 1300 and features a sophisticated epicyclic gearing arrangement. The design of geared astrolabes may also have influenced the development of mechanical clocks which began to appear in Europe around the late 13th century and it is interesting to note that the earliest applications of mechanical clock technology were also astronomy related.

Astronomical Clocks

The design and manufacture of geared mechanisms advanced rapidly in the Middle Ages through the development of the mechanical clock. The initial focus of this effort was the construction of astronomical clocks; elaborate timepieces that also displayed astronomical information, such as the positions of the sun and moon, and which were often accompanied by automata.

The first astronomical clocks originated not in Europe but in China. Although there is evidence of mechanical clock development in China as early as the 8th century AD, the first fully documented astronomical clock was built by Su Sung, a Chinese scholar and engineer who lived during the Song Dynasty at the end of the 11th century. Named the 'Cosmic Engine', the elaborate design featured a time display surmounted by a large mechanised celestial globe which was coupled to an armillary sphere mounted on the top. Like a giant cuckoo clock, the time of day was announced at regular intervals by mechanical automata emerging from a series of windows in the base of the clock accompanied by the sounding of bells, gongs and cymbals.

A critical component of mechanical clocks is the mechanism that regulates the speed of rotation of the gearing, which is known as the escapement. In the Cosmic Engine, Su Sung employed an escapement originally devised by the Buddhist monk and mathematician Yi Xing and the military engineer Liang Lingzan over three hundred years earlier for a mechanised celestial globe built in the year 725. This comprised a large wheel with 36 spokes, each of which was fitted with a water bucket on the end. When a bucket filled with water, it became heavy enough to overcome the resistance of a ratchet-like arrangement of levers, rotating the wheel through one increment and positioning the next bucket to receive water. A system of bronze gears and a chain drive transferred this movement to the other parts of the clock. Two water tanks were also incorporated into the design to ensure that water was supplied to this mechanism at a constant rate of flow.

The Cosmic Engine was completed in 1094 and installed atop a 12 metre high clock tower which stood in the grounds of the Imperial Palace in the city of Kaifeng. This imposing device operated until 1126 when the city was captured by Jurchen invaders. It was then dismantled and moved to the Jurchen capital city of Beijing where it is known to have remained in operation for several more years.

Water-powered mechanisms were superseded from around 1270 by clockwork

mechanisms which employed falling weights as a source of power. These first appeared in Europe but their origins are obscure. Weight-driven mechanisms freed up clockmakers to install clocks in places where water power might not be suitable, such as inside buildings. These clocks continued to display astronomical information but their primary function was now to keep time in places of religious worship such as cathedrals and monasteries.

There are references to the construction of several astronomical clocks in England during the late 13th century, the earliest at Dunstable Priory in 1283, but none of these devices have survived and there are no reliable contemporaneous descriptions of them. The earliest recorded example for which we have detailed information is one begun in 1327 by Richard of Wallingford, a mathematician and astronomer who also served for a number of years as the Abbot of St Albans Abbey.

Richard's design incorporated a large disk showing a map of the constellations which rotated to indicate their positions in the night sky. The position of the sun was indicated by a smaller disk mounted on the end of an arm which rotated around the outside of the star map. The phases of the moon were also represented by a rotating ball with white and black hemispheres that could be viewed through a window on the front of the clock. A separate dial displayed the ebb and flow of the tide at London Bridge. The time of day was indicated by the striking of a bell every hour, with the number of strokes automatically varying according to the number of the hour.

Richard of Wallingford died in 1336 as a result of complications from leprosy and his clock was completed some time after his death. It is known to have survived intact until at least 1534 when it was described by John Leland, antiquarian to King Henry VIII, but is likely to have been dismantled following the dissolution of St Albans Abbey five years later in 1539.

The 14th century saw the rapid spread of mechanical clock technology throughout Europe. One of the most impressive and influential examples of the clockmaker's art was an astronomical clock completed in Italy in 1364 by Giovanni de' Dondi, a professor of medicine at the University of Padua. De' Dondi's clock, which he called an 'Astrarium', comprised a heptagonal-shaped frame approximately 1.3 metres high with dials mounted on each side of the upper section that displayed the positions of the sun, moon and five known planets. The dial representing the sun also incorporated a rotating star map. An eighth dial mounted on one side of the lower section displayed the time of day in 24-hour format and a revolving drum mounted horizontally beneath the upper section indicated important dates in the Christian calendar.

The weight-driven mechanism contained 107 brass gears in a highly sophisticated arrangement which included complex epicyclic gearing and oval gearwheels with irregularly spaced teeth. De' Dondi is reputed to have carried out all of the construction work himself, which took 16 years to complete, but it

is possible that his father Jacopo, who also built clocks, may have assisted him.

Following completion, the Astrarium was acquired from de' Dondi by Duke Gian Galeazzo Visconti and installed in the ducal library of the Castello Visconteo in the city of Pavia. Records show that it was still in existence around 1530 but its ultimate fate is unknown. Fortunately, a set of manuscripts by de' Dondi describing the design and operation of the Astrarium did survive and have provided sufficient information for several modern replicas to be built.

Gear Manufacture

Early gears were crafted by hand using only basic hand tools and a pair of dividers to mark out the spacing of the teeth. This was a painfully slow process which required considerable care on the part of the craftsman and did not lend itself to the production of gears with an odd number of teeth. The invention of the spring-driven clockwork mechanism around the year 1450 facilitated the construction of portable clocks that were better suited to domestic use. As mechanical clocks became more commonplace and a clockmaking industry began to take hold in several European countries, a special-purpose tool known as a wheel cutting engine was developed to simplify the manufacture of gears.

A wheel cutting engine is basically a combination of a dividing plate and a cutter in the form of a rotary file. The dividing plate comprises a circular plate drilled with concentric rings of regularly spaced holes and a spring-actuated pin which locks the plate in the desired position. This ensures the correct pitch between teeth by precisely controlling the rotation of the gear blank when moving to the next tooth position. The rotary file is shaped to incorporate the desired profile of a gear tooth and is used to form the gear teeth individually.

The earliest known use of a wheel cutting engine was by Gianello Torriano, an Italian clockmaker and mathematician. In 1530, Torriano was asked to restore the Astrarium of Giovanni de' Dondi for the Spanish king Charles V who had recently been crowned Holy Roman Emperor. Torriano declined the commission on the basis that the Astrarium was beyond repair but offered instead to construct a new astronomical clock which would surpass it. Torriano relocated to Spain and began work on the design of the clock which would become known as El Cristalino due to the rock crystal windows in the case through which the mechanism could be seen. Completed in 1565, it is reputed to have contained over 1,800 gearwheels but was constructed in less than 4 years due to Torriano's use of a wheel cutting engine.

Torriano's wheel cutting engine predates a similar tool for cutting the teeth of clock gearwheels which was invented in 1673 by the prolific English experimental scientist Robert Hooke. Torriano's engine seems to have been unknown outside of Italy and Spain, and it was Hooke's machine that would become the model for the wheel cutting engines which were later used throughout the clockmaking industry. The advent of wheel cutting engines

not only reduced the time required to manufacture gears but also significantly increased their quality.

The Earliest Calculating Machines

The precise rotational relationship between two meshed gearwheels also lends itself particularly well to the counting of numbers. Therefore, the introduction of precision geared mechanisms of the type found in mechanical clocks made possible the development of machines which could represent large numbers and perform simple arithmetical operations on them. The need for such machines was stimulated by the Scientific Revolution, the quest for scientific knowledge that took place in Europe during the 17th and 18th Centuries, the initial focus of which was the study of the planets and planetary motion.

Leonardo's 'Device for Calculation'

In February 1967, US newspapers announced the discovery in Spain's national library, the Biblioteca Nacional de España, of two lost collections of manuscripts by the great Renaissance artist, military engineer and inventor Leonardo da Vinci. The discovery was made by Jules Piccus, a professor of Romance languages at the University of Massachusetts Amherst. Piccus had been searching the library for medieval ballads and had stumbled upon the long lost manuscripts by chance, much to the embarrassment of library officials. The manuscripts had been brought to Spain in the 1590s and were acquired by the library some time later but had been subsequently misplaced. Now renamed the Codices Madrid, the first collection, the Codex Madrid I, comprised 191 pages of studies in mechanics produced by Leonardo between 1490 and 1496.

News of Piccus's discovery was picked up by Roberto A Guatelli, a New York based Italian engineer who specialised in creating working replicas of Leonardo's designs. On examining a facsimile copy of the Codex Madrid I which had been placed on display at the University of Massachusetts Amherst, Guatelli's attention was drawn to a sketch showing a gear train of 13 parallel vertical shafts, each fitted with a wheel and pinion gear, plus a horizontal shaft at each end of the train to which were attached weights. Annotations suggested a gear ratio of 10:1 between each vertical shaft. He recalled seeing a similar sketch in the Codex Atlanticus, a huge collection of Leonardo manuscripts dating from 1478 to 1519. Convinced that the two sketches represented Leonardo's designs for a calculating machine, Guatelli set out to build a replica based on them.

Following completion in 1968, the replica was exhibited as a 'Device for Calculation' by the US computer firm IBM, which had commissioned models of Leonardo inventions from Guatelli in the early 1950s. However, the exhibit

created controversy in academic circles, prompting an inquiry to be held using a panel of academic experts to ascertain the reliability of the replica. The objectors argued that the Codex Madrid sketch represented a simple device for conferring mechanical advantage, hence the weights at each end, and that Guatelli had used his own intuition and imagination to go beyond what Leonardo had intended. This view was supported by a note written below the sketch in which Leonardo compares the arrangement of gears with one of levers on the opposite page. The findings of the panel of experts were ultimately inconclusive, nevertheless, IBM decided to withdraw the exhibit from display, presumably to avoid any damage to its reputation.

Guatelli's reasoning that the Leonardo sketches were of a calculating device probably stemmed from a strong physical resemblance between the Codex Madrid sketch and later calculating machine designs but this appears to have been purely coincidental. It seems that he and the IBM curators had succumbed to the romantic notion that the creative genius who first conceived such inventions as the helicopter and the parachute should also be responsible for inventing the calculator. There is little doubt that Leonardo possessed the capability to invent such a device. He was an accomplished mathematician and his many designs include a sophisticated automaton in the form of a knight in armour plus a number of clock mechanisms, several of which also appear in the Codices Madrid. He is also known to have studied in the ducal library in Pavia which housed the Astrarium of Giovanni de' Dondi. However, there is nothing in the Codex Madrid sketch to indicate its use for calculation. The Codex Atlanticus sketch is of a more complex mechanism and is much more intriguing but even if it was intended as a calculating device, it is unlikely to have been built as Leonardo seldom bothered to construct his inventions and the Codex Atlanticus manuscripts were not widely seen until relatively recently.

The Calculating Clock

Although no examples have survived, there is compelling documentary evidence to support the case that the first calculating machine was invented by the German astronomer, mathematician, cartographer and theologian Wilhelm Schickard. Schickard was born in the town of Herrenberg near Stuttgart in 1592. Academically inclined from an early age, the first part of his career was devoted to studies in theology and oriental languages at the University of Tübingen and in 1613 he became a Lutheran minister in the nearby town of Nürtingen. However, it was an association with the emerging science of astronomy that led to his work on calculating machinery.

In 1617, Schickard met the mathematician and astronomer Johannes Kepler. Kepler was the leading German astronomer in the early 17th century and a key figure in the Scientific Revolution which swept through Europe during this period. Both men had been educated at the University of Tübingen and shared similar backgrounds and interests. Schickard was also a skilled craftsman

so Kepler asked him to produce some engravings to illustrate his new book 'Harmonices Mundi' which was published in 1619. As their friendship developed, Schickard's enthusiasm for academic studies was reawakened and in 1619 he was appointed to the position of Professor of Hebrew at Tübingen. Kepler also encouraged Schickard's interest in mathematics and astronomy, two subjects that he would have already been familiar with through his undergraduate studies, and the two men began to correspond on a regular basis. It is through these letters that we are aware of Schickard's invention of a calculating machine.

In 1935, the German historian Franz Hammer discovered a letter written by Schickard to Kepler in September 1623 which referred to a machine constructed by Schickard that could automatically perform all four basic arithmetical operations (addition, subtraction, multiplication and division) by means of a geared mechanism. A second letter written in February 1624 provides further details on the design of the machine, which Schickard called a 'Calculating Clock', but also reports that a copy intended for Kepler had been destroyed in a fire at the workshop of the craftsman Schickard had employed to help build it. Frustratingly, two sketches of the machine which Schickard refers to in the second letter were missing. Without these, it was impossible to determine what the machine looked like or how it functioned.

In 1956, while engaged on research aimed at identifying and cataloguing a complete collection of Kepler's works, Hammer made a chance discovery in the library of the Pulkovo Astronomical Observatory in Russia. He was searching through an early copy of Kepler's Rudolphine Tables when he found a slip of paper that had seemingly been used as a bookmark. It was this slip of paper which contained the missing sketches of Schickard's calculating machine.

Hammer announced his findings at an academic conference on the history of mathematics in April 1957. In the audience was Bruno von Freytag-Löringhoff, a Professor of Philosophy at the University of Tübingen and a specialist in the history of logic machines, a type of mechanical device for solving logical expressions. Von Freytag-Löringhoff was inspired by Hammer's revelation that a fellow Tübingen professor may have invented the first calculating machine and he set out to recreate Schickard's design. However, Hammer was a historian and his focus had been on the historical implications of his discovery rather than the mechanical details. Consequently, it was left for von Freytag-Löringhoff to decipher what little source material was available in order to determine how the machine actually operated.

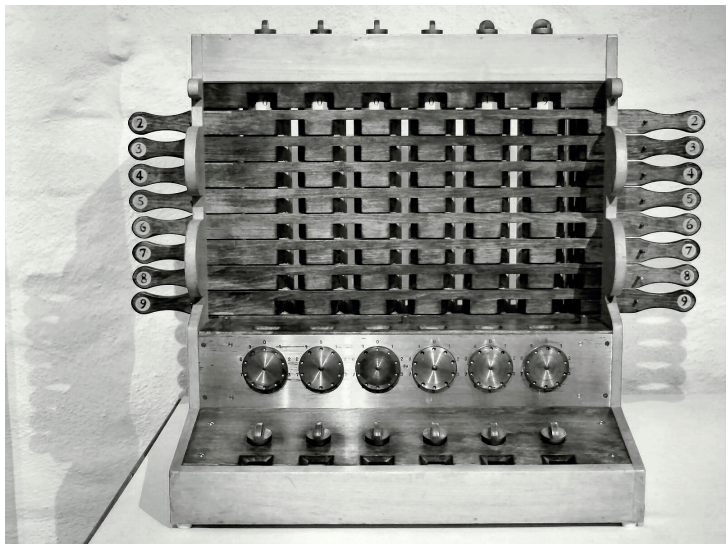
Working over the next three years, von Freytag-Löringhoff, assisted by mechanic Erwin Epple, was able to piece together sufficient information to construct a working replica of Schickard's machine which he publicly demonstrated in January 1960. The Calculating Clock comprised three separate elements; a geared mechanism for the addition and subtraction of six-digit numbers, a

set of Napier's Bones for multiplication and division, and a set of six dials for recording intermediate results. These were all housed one above the other within a single tall box. To perform a multiplication or division calculation, the user first set up the numbers on the Napier's Bones then added or subtracted the partial products using the geared mechanism, utilising the intermediate results dials at the foot of the machine to store the result at each stage in the process.

The addition and subtraction mechanism contained six parallel horizontal shafts arranged in a line to represent the machine's six decimal digits. Each shaft was fitted with a 10-toothed gearwheel and a cylinder with numbers inscribed on its circumference which, when viewed through a small window above, indicated the value of that digit. A dial attached to the front of each digit wheel shaft allowed the numbers which were to be added or subtracted to be set using a stylus. Addition was performed by turning the appropriate digit wheel shaft for the number that you wished to add by the necessary amount using large knobs attached to the front of each shaft, beginning at the rightmost (lowest) digit to be added. Subtraction was accomplished by turning the digit wheel shafts in the opposite direction.

A key feature of Schickard's machine was the method by which it automatically performed a tens carry between digits, a necessary feature for any successful calculating machine design. Schickard could have employed a simple gear train with a gear ratio of 10:1, as had been assumed for the Leonardo da Vinci device, but the cumulative friction from this mechanism would have made the machine very difficult to operate. Instead, he devised a simple carry mechanism which used an additional single-toothed gear mounted on each digit wheel shaft that operated in combination with an intermediate gear to increment the gearwheel representing the next digit to the left by one tenth of a revolution on completion of a full revolution of a digit wheel. However, it is not clear how this mechanism would have coped with the possibility of miscounting due to over-rotation of the intermediate gear. On von Freytag-Löringhoff's replica, this was addressed by the inclusion of a spring-loaded detent that only allowed the intermediate gear to increment by one complete tooth at a time.

We know from a letter written by Kepler to Schickard in 1617 that Schickard was familiar with Napier's Bones through Kepler. In the Calculating Clock, they were implemented using a set of six vertical cylinders with knobs at the top of each to rotate them. In front of these were nine horizontal slides that when correctly positioned revealed windows on the front panel through which the resulting numbers could be viewed. The device for recording intermediate results comprised a set of six disks with numbers inscribed on them, each of which could be rotated via knobs until the desired number appeared in a window.



Replica of Schickard's Calculating Clock (Photo © Herbert Klaeren)

Although astronomical calculations generally require numbers considerably larger than six digits, Schickard may have restricted his machine to only six due to the mechanical limitations of the carry mechanism. The action of adding 1 to the number 999999 would have resulted in a large amount of mechanical stress being placed on the single-toothed gear at the units position due to the cumulative friction from performing a carry at every position simultaneously, possibly causing damage. Therefore, for larger numbers, Schickard provided a set of brass rings for placing over the fingers to remind the user how many carries had been performed beyond the sixth digit. An audible prompt was provided by a bell that rang each time such a carry, or overflow, occurred.

Schickard went on to become Professor of Astronomy at the University of Tübingen in 1631 but there is no evidence that he continued his work on calculating machines. It is possible that he gave up, having been unable to overcome the mechanical limitations of his design but it is also possible that he was satisfied with the performance of the machine and had no reason to develop it further. Sadly, Schickard died of the bubonic plague, aged 43, in October 1635 along with his only remaining child, the disease having also taken the lives of his wife and other children some months earlier. His original machine has never been found.

The Pascaline

Until the discovery of Schickard's letters to Kepler, it was generally accepted that the first calculating machine was invented by the celebrated French mathematician, scientist and philosopher Blaise Pascal. Pascal was born in

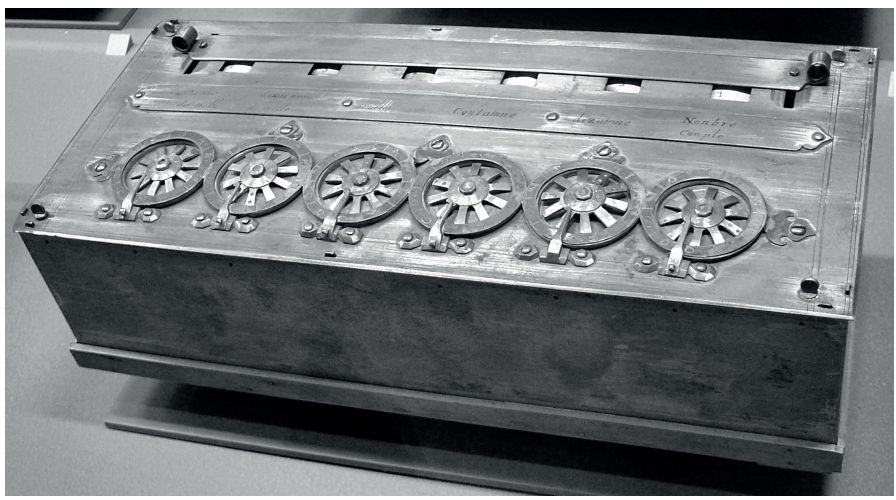
the city of Clermont (now Clermont-Ferrand) in 1623, the same year that Schickard invented his Calculating Clock. Remarkably, the man who would become one of France's greatest scholars had no formal education, having been tutored at home under the direction of his father Étienne, a senior civil servant who had himself dabbled in scientific study. The family moved to Paris in 1631 following the death of Pascal's mother. In Paris, he was introduced by his father to many of the leading French intellectuals of the day. The young Pascal flourished in the stimulating intellectual atmosphere of the Paris salons and he soon acquired a reputation as an exceptional mathematical talent.

In 1639, Pascal's father was appointed royal tax collector for the Upper Normandy region and the family moved to the city of Rouen. There Pascal continued his mathematical studies, publishing his first academic paper, an essay on conic sections, in 1640. In 1642, Pascal began work on the design of a calculating machine in an effort to help his father with the lengthy tax calculations necessary for France's complicated non-decimal system of currency. However, initial attempts to employ local tradesmen to undertake the construction work were unsuccessful. Undeterred, Pascal decided to teach himself the skills necessary for building mechanical instruments and over the next three years he completed the design and construction of his first calculating machine, which he called the Numerical Calculating Machine or 'Pascaline'.

Without access to Kepler's private correspondence, it is highly unlikely that Pascal would have been aware of Schickard's earlier work and this is evident in the design of the Pascaline which differs considerably from that of the Calculating Clock. Pascal's machine was designed to perform addition and subtraction of five-digit non-decimal numbers. It comprised a rectangular brass box about the size of a shoe box, on the lid of which was a row of five spoked wheels for entering numbers. Above each wheel was a small window through which the resulting numbers, which were displayed on numbered cylinders, could be read. The rims of the spoked wheels, which were fixed, were engraved with numerals at each spoke position to represent the value of the digit entered. The number of spokes in each wheel corresponded to the French system of currency at that time, with 12 on the wheel at the right hand end to represent deniers, 20 on the next wheel to represent sols, and 10 at each of the other three positions to represent livres.

Numbers were entered into the Pascaline by means of a stylus which was placed between the appropriate spokes in each spoked wheel and used to rotate the wheel clockwise until a stop fixed to the lid of the box was reached. Successive numbers would then be dialled in to the machine in the same way until the calculation was completed. Multiplication and division were not possible directly but could be performed by successive addition or subtraction until the desired result was achieved.

In order to overcome the problem of undue mechanical stress on the gearwheels when performing multiple carries between digits, Pascal devised an ingenious carry mechanism which employed falling weights. A weighted lever connected to each digit gearwheel was raised incrementally by the action of the rotating gearwheel. On reaching the correct value for a carry, the lever then dropped under gravity, driving a linkage that rotated the next digit gearwheel by one. However, the complex design of this mechanism rendered it unidirectional, so subtraction could not be accomplished by simply rotating the gearwheels in the opposite direction. Pascal solved this problem by employing the 'nine's complement' method, where the nine's complement of the number that you wish to subtract (the number that must be added to each digit to produce nine) is added to the number to achieve the same result. To facilitate this, an additional row of results windows positioned above displayed the nines complement of each number in the window below and a sliding cover was provided to select which row would be visible during a calculation.



The Pascaline (Photo © David Monniaux)

In an effort to refine his design, Pascal constructed numerous versions of the Pascaline over the following seven years, experimenting with alternative materials and changing the specification according to the intended application. Some of these variants were fully decimal and featured up to eight digits but they all employed the same basic mechanism. During this period, Pascal discovered that a local clockmaker in Rouen had constructed a replica of his machine based on a description that Pascal himself had provided. To make matters worse, the clockmaker had attempted to improve the mechanism and seemed intent on selling the machine commercially. Pascal, who was known to be prone to occasional bouts of pomposity, viewed this as an affront to his

reputation. It spurred him into seeking an early form of patent protection for his invention, a royal decree granting him a monopoly on the manufacture and distribution, which he obtained in 1649 after sending one of his machines to the French Chancellor.

Enthused by the prospect of commercialising his invention, Pascal then embarked on a series of promotional activities, including a public demonstration of the machine in Paris. These efforts led to the purchase of two machines by Queen Ludwika Maria Gonzaga of Poland, who was a prominent patron of the sciences. He also gifted one machine to Queen Christina of Sweden, another keen supporter of the sciences, in 1650. Pascal's designs made extensive use of lantern wheel gears, a type of gearwheel which uses cylindrical bars instead of teeth, as these were easier to manufacture than toothed gears. However, the machines remained incredibly time consuming to construct due to the intricacy of the mechanism and the lack of suitable tools for manufacturing precision parts. This necessitated a selling price of 100 livres, the equivalent of a year's salary for a middle income worker, so few examples were sold despite the interest shown in the machine by the scientific literati. Reliability was also questionable, as the gravity-driven carry mechanism was prone to errors if the machine was knocked or moved suddenly during a calculation.

Following a decade of development, Pascal appears to have tired of working on calculating machines, probably through frustration with unsuccessful attempts to make money from his invention. For the next few years he devoted his energies more fully to his scientific and mathematical work, later abandoning these in favour of philosophical and theological studies as a result of a profound religious experience in 1654.

Pascal died at the age of 39 in August 1662 after a lifetime of ill health, his place in history nevertheless assured by his remarkable achievements in mathematics, philosophy and the natural sciences. Fortunately Pascal's work on calculating machines is reasonably well documented. In 1644, he wrote a 16-page pamphlet describing the Pascaline, a copy of which was appended to his letter to the French Chancellor requesting patent protection, and a written account of the machine can also be found in Diderot's Encyclopédie of 1751. Nine of the 50 or so original machines known to have been made by Pascal have also survived.

Although no longer credited as the inventor of the first mechanical calculating machine, Blaise Pascal deserves credit for being first to recognise the commercial potential of calculating machinery. His work also inspired others to create calculators, most notably the English diplomat and inventor Samuel Morland, but none were able to improve significantly on Pascal's design until the invention of the first machine that could automatically perform all four basic arithmetical operations in 1674.

The Stepped Reckoner

The next significant advance in calculating machine technology was made by another prominent figure in 17th century intellectual circles, the German mathematician, philosopher and historian, Gottfried Wilhelm Leibniz. Leibniz was born in 1646 in the city of Leipzig. His father, who died when he was six, had been Professor of Moral Philosophy at the University of Leipzig and this was where Leibniz went at the age of fourteen to study law. A gifted scholar, Leibniz graduated with a Bachelor's degree in 1663, swiftly followed by a Master's in philosophy later that same year. He then began working towards obtaining a doctorate, however, his doctoral thesis was rejected, possibly as a result of his youth, and he transferred to the University of Altdorf where he received a doctorate in law in 1667.

Having turned down the offer of an academic post at Altdorf, his first job upon leaving university was as secretary to the Nuremberg Alchemical Society. However, an interest in politics and a desire to help with his country's recovery from the ravages of the Thirty Years War led to a succession of diplomatic roles, the first of which was in the service of the German statesman Baron Johann Christian von Boineburg. During this period Leibniz also pursued a growing interest in science and this appears to have been the trigger for his work on calculating machines.

Leibniz began work on the design of a calculating machine in 1671. In 1672, he was sent to Paris as diplomatic advisor to the Archbishop of Mainz. Paris had become the intellectual capital of Europe and Leibniz was fortunate to be allowed to remain there for four years. Making the most of the situation, he took the opportunity to improve his knowledge of mathematics and physics by studying under the prominent Dutch scientist Christiaan Huygens, who was also based in Paris at this time. As part of these studies, Leibniz familiarised himself with the works of Blaise Pascal and it is very likely that he also encountered Pascal's calculator designs during this period.

Leibniz soon began to encounter the same problems with construction and materials that his predecessors had faced. He exhibited a wooden model of his calculating machine to the Royal Society in London in January 1673 which, although incomplete, was sufficiently impressive that it helped secure his election as a Fellow in April of that year. However, it was only after he engaged the services of a Paris clockmaker by the name of Olivier that he was able to make further progress and his machine, which he described as a Staffelwalze, or Stepped Reckoner in English, was finally completed in the summer of 1674.

The Stepped Reckoner was designed to perform addition, subtraction, multiplication and division on decimal numbers of up to eight digits with a product of up to twelve. It took the form of a long box-shaped instrument, slightly larger than the Pascaline, which was constructed in brass and steel and mounted in a wooden case. The machine was divided lengthwise into two

parts, an upper section (when viewed from above) containing the calculating mechanism and a lower section containing the input mechanism. On the top face of the lower section was a row of eight small digit setting dials for entering numbers and a larger multiplier dial at the right hand end for setting the multiplicand or divisor required for a multiplication or division calculation. The top face of the upper section featured twelve windows for displaying the results, each of which could also be set to a specific value. A crank handle mounted on the front of the machine allowed the lower section to be shifted lengthwise relative to the upper in order that the eight digit positions at which the input mechanism engaged with the calculating mechanism could be altered by up to four places. A second crank handle at the left hand end operated the calculating mechanism.

Addition and subtraction calculations were performed by entering the first number directly into the results windows, setting the second number using the digit setting dials then turning the crank handle once in a clockwise or anticlockwise direction depending on whether the user wanted to add or subtract. Negative results were displayed as red numbers in the results windows. Multiplication and division were performed by repeated addition or subtraction. For a single digit multiplicand or divisor, this was done by setting the operand using the digit setting dials, then using a stylus to set the multiplicand or divisor on the multiplier dial and turning the crank handle continually until the number set on the multiplier dial had been reached. For multiplicands or divisors with more than one digit, this sequence was repeated for each additional digit with the input mechanism repositioned each time so that it corresponded to the position of the digit in the multiplicand or divisor.

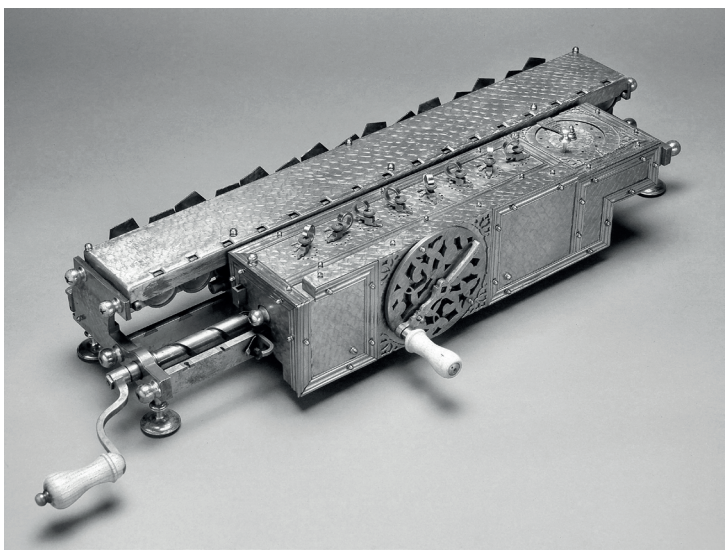
The key component of the Stepped Reckoner was the 'stepped wheel', a cylindrical drum with 9 gear teeth of varying length, arranged so that their length increased as the drum was rotated. This operated in conjunction with a small pinion gear which could be positioned at any one of ten locations along a shaft mounted parallel to the drum so that it meshed with a different number of teeth on the drum depending on its position, ranging from 0 teeth at one end to 9 at the other. The input mechanism contained eight of these stepped wheels, one for each digit, and the positions of the pinion gears for each were controlled by the digit setting dials on the lower section of the machine.

The Stepped Reckoner incorporated a simple tens carry mechanism that employed a series of connecting rods and star wheels to increment the next digit position by one at the appropriate point. Unlike Pascal's design, this mechanism was bidirectional, however, it was incapable of propagating a carry across more than one digit position simultaneously. To solve this problem, Leibniz devised a clever workaround in the form of an indicator device which employed pentagon-shaped disks whose edges were visible through slots in the top of the machine. These were arranged so that they would come to rest with their edges flush when a carry was correctly performed but with a corner

protruding through the slot to indicate when a carry was pending and required user intervention.

Leibniz submitted his completed machine to the Académie des Sciences in Paris in 1675. Two further examples, one of which had an increased product capacity of 16 digits, are known to have been constructed under the supervision of Rudolf Christian Wagner, an associate of Leibniz who was Professor of Mathematics at the University of Helmstedt. Leibniz had also planned to build a machine for the Russian Tzar Peter the Great but there are no records confirming that this was ever produced.

Leibniz died aged 70 in November 1716, having made major contributions in both mathematics and philosophy over a long and highly productive career. However, his later years were overshadowed by a bitter row with arch rival Sir Isaac Newton over the invention of infinitesimal calculus. Although it is now accepted that both men arrived at their versions of calculus independently, the mathematical community sided with Newton and Leibniz's reputation suffered greatly. Unlike other intellectuals of similar stature, Leibniz was not honoured at the time of his death. Only his personal secretary attended his funeral and he was buried in an unmarked grave.



Leibniz's Stepped Reckoner (Photo © Historisches Museum Hannover)

Leibniz's calculating machines were also thought to have been lost until one of them, the 16 digit machine, was discovered in an attic of Göttingen University in 1876 by workmen repairing the roof. It had been sent there for repair in 1764 and subsequently forgotten. This machine was placed in the collections of the State Library in Hannover but was found to be inoperable due to corrosion and

missing parts. In 1894, it was sent for restoration to Arthur Burkhardt, the proprietor of a successful calculating machine firm based in the German town of Glashütte. Burkhardt worked over the next two years to restore the machine to working order and wrote this up in a detailed account which was published in 1897.

With its ability to perform all four basic arithmetical operations, the Stepped Reckoner was a major leap forward in mechanical calculating technology and the stepped wheel would become a standard component of later calculator designs. It next appeared in a machine constructed by the German clergyman and inventor, Philipp Matthäus Hahn, in 1774. Hahn built several calculating machines before his death in 1790, all of which incorporated the stepped wheel. However, although Leibniz gave a brief description of the operation of the Stepped Reckoner in a 1710 paper, no details of the mechanism were available until the publication of Burkhardt's article almost two centuries later. Therefore, unless Hahn had access to one of the Leibniz machines (and there is no evidence to support this), it is unlikely that his machines were based directly on Leibniz's work. A more plausible scenario is that Hahn had somehow reinvented the stepped wheel and that later designers had borrowed the concept from Hahn.

Building Blocks – Machine Tools and Mass Production

Despite the pioneering efforts of Schickard, Pascal and Leibniz, it would take more than a century before calculating machines would begin to permeate society. The main reasons for this lengthy hiatus were the difficulty in manufacturing the precision components necessary for such machines and the resulting high cost of manufacture. Both were alleviated by the development of machine tools and mass production techniques during the Industrial Revolution.

The Evolution of Machine Tools

Tools for cutting or shaping material have been used for many thousands of years and the origins of the machine tool can be traced back to the woodworking lathes developed by the ancient Egyptians around 1250 BC. In its simplest form, the lathe is a device that rotates a block of material between centres, allowing cutting tools to 'machine' the material to form cylindrical shapes in a process known as turning. Early lathes were hand operated and required an additional person to rotate the workpiece back and forth by means of a rope or a bow. Foot treadle lathes that required only a single operator began to appear in the 13th century. The earliest versions retained the use of the rope drive which was supported from above by a flexible pole and operated by a foot treadle. This was later replaced by a flywheel and crank mechanism to rotate

the workpiece in a unidirectional motion.

The addition of a heavy flywheel and the faster speeds achievable through continuous rotation made lathes much more powerful, thus extending their capability, and the first lathes for cutting screw threads in wood were developed in Germany in the late 15th century. The earliest depiction of a screw-cutting lathe appears in the Mittelalterliche Hausbuch, an important medieval manuscript which was completed around 1480. This incorporated a slide rest to support the cutting tool, the position of which could be accurately controlled by means of two screws; the lead screw to move the tool longitudinally along the length of the workpiece, and the cross feed screw to move the tool towards or away from the workpiece in a transverse motion. Leonardo da Vinci is also known to have produced designs for various machine tools during this period and his sketches for a foot treadle lathe, a screw-cutting lathe and a pipe boring machine appear in the Codex Atlanticus.

The next significant advance in machine tool technology also took place during the 15th century when water power was first applied to machine tools. This further increased the power of the tools to the point where they could be successfully applied to metalworking. The driving force for these applications was the European armaments industry, particularly the manufacture of cannon, the demand for which grew rapidly as nations began to increase the size of their navies.

Early cannon had been manufactured by forging strips of wrought iron into a cylindrical shape in a process similar to barrel making but these crude weapons were unreliable and the technique was limited to the manufacture of smaller calibre weapons. The trend towards larger and more powerful weapons led to the introduction in the early 16th century of cannon which were cast from iron or bronze using a process adapted from one used to cast bells. However, the casting process produced a bore which was insufficiently smooth and cylindrical. This prompted the development of a new type of machine tool known as a boring mill.

A boring mill is essentially a lathe which has had one of its centres replaced by a long bar with a cutting tool on the end. In early designs, the workpiece would be held stationary while the rotating boring bar was fed slowly into the bore of the cannon to allow the cutting tool to machine it to a smooth finish. One of the earliest depictions of a cannon boring mill is given in the Pirotecnia, a treatise on metals and metallurgy written by the Italian engineer and metallurgist Vannoccio Biringuccio, which was published in 1540. Biringuccio's boring mill was driven by a type of treadmill powered by the action of two men walking inside it but the similarity to a water wheel is striking and it is often described as being water powered.

Early boring mills were designed to finish a pre-existing bore that had been formed by casting and were incapable of correcting common defects, such as

where the bore was badly misshapen or had been cast eccentric to the body of the cannon. This deficiency was rectified in 1713 by the Swiss inventor Johann Maritz. While employed as Commissioner of the King's Foundry in Strasbourg, France, Maritz invented a new type of vertical boring mill that was capable of machining cannon from solid castings. In Maritz's design, the workpiece was suspended vertically over the boring bar mechanism which was driven by two horses. Maritz continued to refine his design after moving to the Netherlands where the technique of boring from solid castings was eventually adopted for all cannon manufacture.

Development of the cannon boring mill continued throughout Europe and in 1774 the English industrialist John Wilkinson patented a horizontal boring mill that offered improved accuracy. In Wilkinson's water-powered design, the workpiece was positioned horizontally and rotated between bearings while the stationary boring bar was fed into it by means of a rack and pinion mechanism. This arrangement helped to increase rigidity and reduce vibration, resulting in a more precise machining action. Wilkinson's patent was revoked in 1779 due to an embarrassing similarity to an earlier machine invented by the Dutch foundryman and artist Jan Verbruggen in 1758. Undaunted, Wilkinson had already adapted his machine for a different purpose, one which would help to realise the most important invention of the Industrial Revolution.

In the same year that Wilkinson patented his boring mill, the Scottish steam engine pioneer James Watt entered into a historic partnership with an English businessman to commercialise a new design of engine which he had patented five years earlier in 1769. Watt's condensing steam engine was aimed at improving the efficiency of the Newcomen engine and relied on cylinders with a very accurate bore in order to maintain pressure and prevent the steam from escaping. Having worked for several years as an instrument maker, Watt had little difficulty in producing a working model of his steam engine. However, building a full-scale engine was another matter, as cannon boring mills were unable to provide the necessary accuracy and there were no other machine tools available that could perform this task.

Fortunately, Watt's business partner Matthew Boulton was acquainted with John Wilkinson through their mutual membership of the Lunar Society, a dinner club of prominent industrialists and intellectuals which met in Birmingham during this period, and was aware of Wilkinson's work on precision boring mills. After being introduced to Watt, Wilkinson agreed to adapt his cannon boring mill to make it suitable for machining a cylinder to Watt's exacting requirements. Having proved that it could be done, Wilkinson then devised a new type of boring mill specifically for steam engine cylinders.

Wilkinson was rewarded for his efforts by being appointed sole supplier of cylinders to the firm of Boulton & Watt and James Watt's efficient steam engines went on to play a pivotal role in the Industrial Revolution, providing

a ready source of power for all manner of industrial machinery including machine tools themselves.

Precision Machine Tools

Wilkinson's cylinder boring mill of 1776 heralded the dawn of a new era of precision engineering. However, the development of precision machine tools was also driven by clock and watch making, in particular the demand for smaller and more accurate timepieces, and by the manufacture of scientific instruments. At the forefront of these developments was the English mathematical and astronomical instrument maker Jesse Ramsden.

In 1767 Ramsden invented a new type of circular dividing engine, a specialist machine for engraving accurate graduated scales, which incorporated a worm and wheel mechanism to rotate the workpiece through the desired angle. The accuracy of this mechanism was dependent upon the uniformity of the thread pitch of the worm screw and the closeness of the mesh between it and the teeth of the worm wheel. In order to manufacture a worm screw of sufficient accuracy, the talented and resourceful Ramsden also designed and built the first successful precision screw-cutting lathe.

To cope with the hardened steel material of the worm screw, Ramsden's lathe employed rigid metal construction and a diamond tipped cutting tool. It also implemented an idea first seen in Leonardo da Vinci's sketch of a screw-cutting lathe over two hundred years earlier; a set of 'change wheels' which altered the gear ratio between the spindle and the lead screw in order to change the thread pitch of the screw being cut. Ramsden used his new lathe to machine two examples of the worm screw, one of which he then modified by creating sharp notches in the threads. He then used the modified screw as the cutting tool when machining the teeth of the worm wheel, thus ensuring a precise fit.

In 1774 Ramsden constructed a larger circular dividing engine which also incorporated improvements to his original design. For this second machine, Ramsden was awarded the tidy sum of £615 from the Board of Longitude, the British government body established in 1714 to solve the problem of discovering longitude at sea. The award was made in recognition of the new machine's potential for improving the accuracy of maritime navigation instruments such as the sextant. However, a condition of acceptance was that Ramsden must make the design publicly available along with that of his precision screw-cutting lathe.

Ramsden also designed a second screw-cutting lathe in which the lead screw engaged with a circular toothed plate which controlled the movement of the tool. This too was placed in the public domain. His final version, completed in 1778, was the culmination of more than a decade of development, with each model used to machine the lead screw for successive versions, thereby improving the accuracy through each iteration of the design. The Board of

Longitude award conditions helped ensure that Ramsden's innovative machine tool designs were adopted by other instrument makers of the period, thus advancing the art enormously.

Ramsden's designs may also have influenced the work of Henry Maudslay, the British engineer who was the most influential of all the machine tool pioneers. In his screw-cutting lathe of 1797, Maudslay brought together earlier developments into a single machine tool that is the direct ancestor of all modern lathes. Maudslay's elegant design employed a pair of parallel triangular bars which served as guideways for the slide rest. A lead screw, which was positioned between the guideways, could be coupled to the carriage supporting the slide rest by means of a split nut and clamp arrangement. Maudslay also included an adjustable tailstock and backrest to accommodate long workpieces and to provide adequate support against the thrust of the cutting tool.

Like Ramsden before him, Maudslay continued to refine the design of his screw-cutting lathe in a quest to improve the accuracy of his workmanship. His second version, completed in 1800, featured flat guideways and a set of 28 change wheels to accommodate a wider range of thread pitches. In his third design he combined triangular and flat guideways, and added stepped drive pulleys to allow the speed of rotation to be varied. With this machine tool, he was able to manufacture a precision screw 5 feet long with an extremely fine pitch of 50 threads per inch. This screw was sufficiently accurate that it was used for calibrating astronomical instruments.

Despite the obvious commercial potential of these designs, Maudslay had little interest in producing machine tools for sale, preferring instead to remain in the business of running a successful engineering workshop. This provided an opportunity for another firm to establish a market by introducing the first commercially available machine tools. The first to do so was Holtzapffel & Co., a firm founded in London in 1794 by John Jacob Holtzapffel, who had worked for Jesse Ramsden for two years after emigrating from France. Holtzapffel & Co specialised in lathes for ornamental turning, a popular pastime during this period, and the company sold its first lathe in June 1795.

Machine tools for industrial use were introduced by the Leeds-based firm of Fenton, Murray & Wood around 1800. Originally a competitor of Boulton & Watt in the steam engine business, the company began supplying cylinder boring mills to external customers including Portsmouth naval dockyard and a French engineering works. Other manufacturers soon followed and by 1820 a sizeable machine tool industry had been established.

Measuring Instruments

Progress in precision engineering was also dependent on the development of accurate measuring instruments to ensure that parts were manufactured to the correct size. Instruments based on graduated scales, such as rulers and

slide callipers, had been in use for centuries but these were inadequate for measuring to the accuracy that the new precision machine tools were capable of. Fortunately, the advent of precision screws for use in machine tools also facilitated the development of more advanced measuring instruments based on the ability of a screw to effect precise linear dimensions using the rotational movement of the screw to subdivide its pitch. The first of these was the micrometer.

In its simplest form, a micrometer comprises a u-shaped calliper frame fitted with a fixed anvil at one side and a moveable anvil on the end of a fine pitch screw, or spindle, at the other. Measurements are made by adjusting the spindle until the object is lightly held between the anvils. The resulting dimension is then read by adding the value indicated on a circular scale on the thimble of the spindle to the value shown on a linear scale on the barrel.

The principles on which the modern micrometer is based were established by the English astronomer and instrument maker William Gascoigne in 1639. In an effort to measure angular distances through an astronomical telescope, Gascoigne devised a set of callipers that appeared in the field of view of the telescope. A precision screw, incorporating a left hand thread on one half and a right hand thread on the other, allowed the gap between the jaws of the callipers to be finely adjusted. Measurements were made by counting the number of complete revolutions of the screw and reading the fraction of a revolution turned using a circular scale mounted on the end of the screw. By knowing the optical magnification of the telescope, Gascoigne was also able use this device to measure the diameter of the moon and stars.

This combination of a calliper and precision screw was first adopted for engineering measurement by the steam engine pioneer James Watt. In 1772, Watt built a benchtop instrument for his own personal use. It comprised a u-shaped brass frame fitted with fixed and moveable steel anvils, with a large dial and crank handle at one end and a smaller dial on the front. The moveable anvil took the form of a horizontal slide which was adjusted by means of a rack and pinion mechanism. This was operated by turning the crank handle, with the number of complete revolutions of the pinion indicated by a pointer on the smaller dial and fractions by a scale on the large dial with graduations representing increments of one thousandth of an inch. Watt's measuring instrument is the first known example of a bench micrometer.

A bench micrometer was also constructed by the machine tool designer Henry Maudslay in 1805. Maudslay's design was intended for high accuracy measurement and dispensed with the calliper frame in favour of a gunmetal bedplate more reminiscent of a small lathe. This supported two saddles fitted with anvils, one of which was fixed and the other connected through a slot in the bedplate to a very fine pitch screw of 100 threads per inch. A large knob on the end of the screw was engraved with a scale divided into 100 graduations.

A graduated scale on the bedplate indicated the number of complete revolutions for a given dimension. Capable of measuring to a resolution of one ten-thousandth of an inch, Maudslay nicknamed his micrometer the 'Lord Chancellor' for its ability to serve as an arbiter in disputes between his employees over the accuracy of their workmanship.

The development of the micrometer into the familiar handheld instrument of today was made by the French engineer Jean Laurent Palmer. Palmer designed his screw calliper as an instrument for measuring the thickness of sheet metal and obtained a French patent on his design in September 1848. With a 20 mm range and 0.05 mm resolution, Palmer's design incorporated most of the features of a modern outside micrometer.

Palmer exhibited his screw calliper at the 1867 Paris Exposition where it was seen by Joseph R Brown and Lucian Sharpe of the US machine tool firm Brown & Sharpe on a visit to France in August of that year. The two men had been approached a few months earlier by an inspector from a brass plate manufacturer who had presented a number of alternative designs for a gauge that could reliably measure the thickness of sheet metal in an effort to avoid potential disputes with customers. They realised that Palmer's design offered a better solution to the problem and the following year Brown & Sharpe introduced the world's first mass produced micrometer, an improved version of Palmer's design with a finer pitch screw and a clamp to lock the spindle. Now every machine shop had the means to measure their work accurately, with the result that quality improved significantly.

Interchangeability and Mass Production

The powerful combination of precision machine tools and measuring instruments led to the realisation of the principle of interchangeability, where components are manufactured with such precision that they can be swapped with other examples of the same component without having to alter them to make them fit. Interchangeability simplifies manufacturing by removing the need for custom fitting of parts, thereby speeding up the assembly process and reducing the requirement for skilled labour.

The idea of interchangeability was first proposed by a French army officer, Lieutenant General Jean-Baptiste Vaquette de Gribeauval. In 1765, Gribeauval initiated a process of rationalising and standardising French field artillery which became known as 'le système Gribeauval', the ultimate goal of which was to achieve interchangeability throughout the full range of armaments. After experiencing early success with interchangeable gun carriages, Gribeauval reasoned that if this was extended to small arms, which were more complex, they could be manufactured faster and more economically. Interchangeable parts would also make field repairs much easier to carry out and would extend the service life of small arms considerably.

While in the course of implementing his reforms, Gribeauval learned that a French gunsmith, Honoré Blanc, was already experimenting with interchangeable parts for muskets. Blanc had recently designed a new version of the popular Charleville musket for the French infantry, the Model '77, which had been well received. By now Gribeauval had risen to the post of Inspector General of Artillery for the entire French Army. He used this authority to appoint Blanc inspector of three Royal arsenals and asked him to redouble his efforts on interchangeability.

By 1785 Blanc had succeeded in producing a batch of interchangeable musket locks and was planning to extend his methods to include the other parts of a musket. As precision machine tools were not yet available commercially, he employed a combination of die casting and templates or jigs to guide the hand finishing process. The following year Gribeauval provided the funding for Blanc to set up a factory and increase production but Gribeauval's death in May 1789 and the start of the French Revolution later that same year put an end to Blanc's status as a government contractor and the enterprise foundered.

Fortunately Blanc's work on interchangeability had caught the attention of the American statesman Thomas Jefferson, who served as US Ambassador to France from 1785 to 1789. Jefferson had visited Blanc's workshop in August 1785 and was given a hands-on demonstration in which he was invited to assemble a musket lock from a selection of 50 of each part chosen at random. When the parts fitted perfectly, Jefferson realised that Blanc's interchangeability system offered a solution to the chronic shortage of skilled craftsmen in the fledgling US armaments industry, which required the country to import most of its weapons from Europe, and wrote enthusiastically about it in a letter to the US Foreign Secretary. Three years later, as the political situation in France began to deteriorate, Jefferson approached Blanc with an offer to relocate him and his work to the US but Blanc declined. Instead Jefferson purchased six of his muskets and sent them to the US Secretary of War as an example of what had been achieved along with a recommendation that Blanc's methods be adopted by US armouries. However, Jefferson's recommendation would not be acted upon for several years.

In June 1798, the American inventor Eli Whitney won a major contract from the US government to supply 10,000 muskets to the War Department within a two year delivery period. Whitney was facing financial ruin following a disastrous attempt to protect and exploit his invention of the cotton gin and was the first businessman to take advantage of the US government's willingness to provide generous cash advances on major armaments contracts in preparation for a possible war with France. Despite having no factory, no workers and no experience in gun manufacturing, Whitney secured the $134,000 contract, and its $10,000 advance, on the back of a compelling vision of water-powered machine tools to significantly reduce the amount of skilled labour required.

Whitney began by setting up an armaments factory in New Haven, Connecticut and visiting established US armouries in order to learn their methods. However, building the necessary machine tools and training a new workforce to operate them was a huge undertaking and he soon fell behind schedule. In an effort to help him, Thomas Jefferson, who was a personal friend, told Whitney about Honoré Blanc's work on interchangeability and another friend, US Treasury Secretary Oliver Wolcott, sent him a copy of a paper written by Blanc in 1790. This information was the lifeline that Whitney needed and he wasted no time in taking Blanc's methods and incorporating them into his own concept of manufacturing which he named the Uniformity System.

Whitney conducted a demonstration of his Uniformity System in January 1801, fitting ten preassembled musket locks to the same musket in front of an audience of senior US government officials which included the now Vice President Thomas Jefferson and President John Adams. The success of this demonstration bought Whitney some time until he was able to deliver the first batch of 500 muskets the following September. However, tests conducted on surviving examples of Whitney's muskets have shown that they do not contain interchangeable parts and it now seems likely that the demonstration was faked.

Whitney continued to struggle with delivery timescales and it took him a further eight years to complete the contract. Nevertheless, he deserves credit for introducing the principle of interchangeability to America. Encouraged by the US government, which now insisted that all armaments contracts specify interchangeable parts, Whitney's Uniformity System was adopted throughout the US armaments industry. It was eventually perfected by the US firearms manufacturer John H Hall at the Harpers Ferry armoury in 1827 and became known as the American System of Manufacturing. Hall developed various special purpose machine tools which he utilised to finish parts produced by die casting and drop forging. This was augmented with a system of carefully designed fixtures to position parts accurately during machining and gauges to inspect the finished parts. The combination of precision machining and accurate measurement allowed Hall to obtain the consistency of manufacture that had eluded Whitney.

By adopting the American System of Manufacturing, individual firms were able to achieve interchangeability for their own products. However, interchangeability between different manufacturers was far more challenging. Achieving this would require not only the introduction of recognised standards for common parts but also standards for the measurement of length to ensure that measurements made with different instruments were consistent. The central figure in these developments was the British mechanical engineer Sir Joseph Whitworth.

Whitworth had learned his trade working for the great Henry Maudslay

and in 1833 he established his own machine tool manufacturing business in Manchester, rising to become the foremost machine tool builder in the country. In later years he also moved into armaments manufacture. Throughout his long career Whitworth strove to improve standards of accuracy in engineering manufacture. He was among the first to recognise the importance of calibration, where measuring instruments are compared against one of greater accuracy in order to assess performance or improve accuracy by using the information obtained to correct subsequent measurements made with that instrument.

At the Great Exhibition of 1851 Whitworth exhibited a length measuring machine which could detect differences of one millionth of an inch. He used this machine to compare the length of his own standard yard bar with that of the official government standard. He also developed a technique for producing accurate flat surfaces which could be used as reference planes. This work led to the establishment of a system of traceability to national standards of length.

The advent of screw-cutting lathes and other thread forming tools during the Industrial Revolution allowed threaded fasteners such as screws and bolts to be manufactured by machine rather than by hand, thus ensuring uniformity. However, thread sizes differed from manufacturer to manufacturer which hindered interchangeability. Whitworth proposed a standard system for screw threads in 1841. It featured a fixed thread angle of 55 degrees and a standard pitch for a given diameter. The specifications were based on a sample of screws collected from a large number of manufacturers which were measured to obtain their average values. Whitworth's rationalised system of screw threads was in general use throughout Britain by 1860 and other nations soon followed with their own systems of screw thread standards.

Interchangeability and standardisation provided the foundations for the spread of mass production from armaments manufacture to domestic products such as clocks and watches, sewing machines and bicycles. It also facilitated the successful commercialisation of calculating machines.

The Arithmometer

The new machine tools and mass production techniques introduced during the Industrial Revolution offered the prospect of reducing the manufacturing cost of calculating machines to a level where they would no longer be merely toys for the amusement of wealthy patrons. However, production would only be economically viable if there was also a market need for such devices. Fortunately, the Industrial Revolution provided this too due to the immense increase in commercial activity and in international banking that took place during this period. The stage was now set for the foundation of a new industry, the first champion of which was the French businessman and inventor Charles Xavier Thomas de Colmar.

The son of a doctor, Charles Xavier Thomas was born in 1785 in the town of Colmar in the Alsace region of France. In 1809 he joined the French military as an administrator, swiftly rising to Inspector of Supply for the entire French Army. His duties as an administrator involved making lengthy calculations and it was while serving in the Army that Thomas first had the idea of building a calculating machine. After leaving military service in 1819, Thomas obtained a position as General Manager of the Phoenix insurance company in Paris. The complex actuarial calculations that he encountered in his new job provided further evidence of the need for mechanising the calculation process and the following year he designed his first calculating machine, a four function decimal calculator which he named the Arithmometer.

The Arithmometer closely resembled Leibniz's Stepped Reckoner, not only in its outward appearance but also internally due to the use of stepped wheels and a sliding carriage. However, given the dearth of published material on the Stepped Reckoner at this time, it seems more likely that Thomas had seen the machines of Philipp Matthäus Hahn rather than being influenced directly by the work of Leibniz. Also,unlike the Stepped Reckoner, Thomas's tens carry mechanism was capable of propagating a carry across multiple digit positions simultaneously.

The input capacity of the Arithmometer was 3 digits which were set by a trio of sliders. An additional slider was provided for setting the single digit multiplicand or divisor. This controlled a mechanism that automatically performed the repeated addition or subtraction operations necessary for multiplication and division. The calculating mechanism was operated by pulling on a silk ribbon and results were indicated by means of a 6 digit display that featured two sets of results windows, one revealing a dial with increasing values for addition and the other showing one with decreasing values for subtraction. A sliding cover was also provided to select which set was visible during a calculation.

Thomas had a prototype of the Arithmometer built for him by a Paris clock and instrument maker named Devrine. He also took steps to protect his invention by applying to the French Minister of the Interior for a patent in October 1820 which was granted the following month. He then submitted it for review to the influential Société d'Encouragement pour L'Industrie Nationale in Paris in 1821, where it received a favourable report in the Société's bulletin.

After a second prototype was completed in 1822, Thomas appears to have set aside work on the Arithmometer in order to concentrate more fully on his business activities. By 1829 he had established his own insurance firm, Compagnie du Soleil, which was based in Paris. Thomas had spotted a gap in the French market for a company that specialised in fire insurance and he was able to build this business up over the next two decades through a series of acquisitions and mergers, becoming a rich man in the process. This wealth would help to bankroll his later calculator development work.

Thomas returned to calculator development in 1844, exhibiting another Arithmometer prototype at the French Industrial Exposition held in Paris that year. He then teamed up with a watchmaker from Neuilly-sur-Seine named Piolaine and the two men developed an improved model which replaced the flimsy silk ribbon with a metal crank handle and helical gear mechanism. Capacity was increased to 5 digits for input and 10 digits for display, and a reversing lever was added to select addition or subtraction. The redesign was completed by July 1848 and Piolaine was given responsibility for setting up a workshop and putting the new model into production. Piolaine also began to refine the design to make the machine more suitable for mass production but he died unexpectedly a few months later.

Fortunately Piolaine's assistants were able to complete the construction of one of the production prototypes that he had been working on before his death. Thomas exhibited this machine at the Exposition of the Second Republic in Paris in 1849, where it was awarded a silver medal, but without any practical engineering experience he was unable to put it into production. A solution was found in November 1850 when Thomas formed a partnership with another skilled craftsman, A M Hoart, for the purposes of manufacturing Arithmometers. Thomas's original 1820 patent had lapsed after 5 years so he obtained a new French patent in December 1850 and also applied for a British patent early in 1851 in anticipation of exhibiting the Arithmometer at the Great Exhibition in London. He then embarked on a publicity campaign, seizing every opportunity to publicly exhibit his machine and also presenting elaborately decorated examples to European royalty. This generated considerable personal recognition for Thomas in the form of numerous awards and honours, including the prestigious title of Officier of the Légion d'Honneur. Sales of the Arithmometer also began to pick up and by 1854 around 250 machines had been manufactured.

A further revision of the Arithmometer design was undertaken in 1858 which introduced a zero setting mechanism for the results display. The intricate mechanism for automatic multiplication and division was also replaced with a much cheaper to manufacture single digit display that merely kept count of the number of repeated addition or subtraction operations performed. Despite these improvements, by 1865 sales were beginning to flag and the total number of machines produced had only reached 500. Sales then received a boost after Thomas exhibited an Arithmometer at the Paris Exposition of 1867, resulting in the production of a further 300 machines by 1870.

Following Thomas's death in March 1870, Arithmometer production continued under the direction of his son, Louis Thomas de Bojano. By 1878 over 1,500 had been produced. More than half of these went to overseas customers, such as the Prudential Assurance Company in the UK which purchased 24 machines.

Promotional literature from 1855 boasted that Thomas had spent the

enormous sum of 300,000 francs on developing the Arithmometer. However, with a typical selling price of 500 francs and total sales of only 1,500 units over a lengthy period of 28 years, it is unlikely that he ever made a profit from it. Nevertheless, Thomas had demonstrated the commercial potential of calculating machinery and other manufacturers, such as Burkhardt in Germany and Elliott Brothers in Britain, soon followed, producing and selling similar machines in greater numbers.

The 1870s brought a plethora of alternative calculator designs and the establishment of major calculating machine industries in Germany and the USA. Besides the banking and insurance sectors, early customers included scientists, engineers and civil servants. The industry also benefitted from the gradual mechanisation of office work which began with the introduction of typewriters and cash registers around 1874. By the turn of the century the larger firms were each producing thousands of calculating machines per year and the subsequent reduction in manufacturing costs through economies of scale further served to open up new markets.

The Engines of Charles Babbage

In the same year that Thomas patented his first Arithmometer prototype, a young British mathematician by the name of Charles Babbage was embarking on a journey which would stretch the potential of calculating machinery far beyond that envisaged by Pascal and Leibniz. Babbage had recognised that the technology employed in calculating machines held the promise of being capable of much more than simple arithmetic. However, realising such capability would be a formidable intellectual and engineering challenge that would consume the greater part of his adult life.

Charles Babbage was born in London in December 1791. His father's career path, first as a goldsmith and then as a banker, ensured that the family were far from poor but they became very wealthy after his father accepted a partnership in the newly established bank of Praeds, Digby, Box, Babbage & Company in 1801 which he then sold two years later. Charles was a sickly child and this was reflected in his somewhat haphazard education, a mixture of private tutoring and public schooling conducted between Enfield in north London, Cambridge and the family home in rural Devon where he was often sent to recuperate. His schoolmaster in Enfield was a keen amateur astronomer and is thought to have been responsible for sparking Babbage's lifelong passion for mathematics. Though he was given to occasional flights of fancy, Babbage proved to be an able pupil and made efforts to familiarise himself with many of the classic mathematical texts of the 18th century.

In October 1810, Babbage enrolled at Cambridge University to study mathematics and chemistry. However, he was unenthused by the rigid

teaching methods and limited knowledge of his tutors at Cambridge and his attention soon wandered. Babbage possessed a gregarious personality and this led to him becoming involved in various clubs and associations, few of them serious until, in May 1812, he co-founded the Analytical Society with six fellow students and one of their tutors.

The aim of the Analytical Society was to cultivate an analytical approach to calculus which was popular amongst European mathematicians but had been largely ignored in Britain, where mathematical research had stagnated in the giant shadow of Sir Isaac Newton. The Society's first task was to promote the use of the Leibniz notation for infinitesimal calculus as opposed to the more commonly used Newton version. One of his fellow co-founders was John F W Herschel, son of the famous astronomer Sir William Herschel. The Society failed to gain wider acceptance and was dissolved in 1813 but Babbage and Herschel's friendship would become a lifelong one.

Upon graduating with an unremarkable Bachelor's degree (due in part to his extracurricular activities), Babbage left Cambridge in the summer of 1814. A few weeks later he married Georgiana Whitmore, who he had met two years earlier, and set up home with his new wife in the Devon village of Chudleigh. Babbage sought employment in the local mining industry but was unsuccessful and after a few months the couple relocated to London where Babbage proceeded to apply for various academic positions, again without success. However, Babbage was fortunate to possess a private income in the form of a generous allowance of £300 per year from his father plus a smaller one from his father-in-law and this allowed him to indulge his love of mathematics without the worry of having to earn a living from it.

With the help of the Herschels, Babbage soon began to make a name for himself in London intellectual circles. Steady progress in his mathematical studies resulted in a number of well received papers on the theory of functions and he was invited to give a series of lectures on astronomy at the Royal Institution. This culminated in his election as a Fellow of the Royal Society in March 1816, aged only 24.

Babbage's interest in astronomy and astronomical instruments also grew during this period and in February 1820 he and his friend John Herschel were once again involved in the genesis of a learned society. Along with eleven others, they founded the Astronomical Society of London to encourage and promote the science of astronomy, a subject poorly represented by existing organisations such as the Royal Society, which some felt had become more of a gentlemen's club than a serious scientific institution. Renamed the Royal Astronomical Society in 1831 on receipt of a royal charter from King William IV, this would be a much more influential and long-lived body than Babbage and Herschel's earlier effort. It would also provide the impetus for Babbage's first foray into the world of calculating machinery.

One of the first matters that the Astronomical Society concerned itself with was the production of astronomical tables. In the absence of readily available calculating machinery, numerical tables were an invaluable tool for all sorts of calculations ranging from scientific research to banking and navigation at sea. In astronomy, they were used in the calculation of planetary positions, lunar phases, eclipses and calendrical information. However, the production of numerical tables was an arduous task and errors were common. As the Industrial Revolution progressed and society's reliance on numerical tables increased, the reliability of such tables became an issue of national importance.

As the two most talented mathematicians amongst its founder members, Babbage and Herschel were asked by the Astronomical Society to oversee the task of preparing the new tables. However, despite careful planning and the use of two clerks to calculate each entry twice, Babbage and Herschel found that the completed tables contained numerous errors. While discussing errors in one of the tables, Babbage is reported to have said to Herschel "I wish to God these calculations had been executed by steam", to which Herschel replied, "It is quite possible". Babbage's own account of this epiphany from his memoirs describes an earlier occasion while still a student at Cambridge in which he began daydreaming about calculation by machinery while contemplating a table of logarithms. Some historians have questioned the reliability of Babbage's account which was written many years later but what is agreed is that by 1821 Babbage had begun work on the design of his first calculating machine.

The Difference Engine

Babbage was convinced that machinery was the key to producing error-free numerical tables. He envisaged a machine that would not only calculate correctly but would also print the results automatically, thereby also eliminating transcription and typesetting errors. He took inspiration from the heroic efforts of the French civil engineer Baron Gaspard de Prony to produce logarithmic and trigonometric tables for the French government following the introduction of the metric system in 1791. De Prony had employed a large team of people to perform the calculations manually. These were organised into three groups according to ability and the work divided up to suit. This hierarchical approach was made possible through the use of the method of finite differences, where a continuous mathematical function is represented by a polynomial series, the successive values of which can be calculated by adding the first, second, third and possibly higher order differences between each value until the differences become constant. As this method uses only arithmetical addition and subtraction, it removes the need for multiplication and division, thus reducing the likelihood of errors. Production of the tables remained, however, a major undertaking which took nine years to complete.

Babbage may also have been influenced by the work of the German military

engineer Johann Helfrich Müller. Müller had successfully constructed a four function calculator in 1784 which, although capable of calculating to 14 digits, closely resembled the machine built by Philipp Matthäus Hahn a decade earlier. His next idea was much more ambitious. In a letter to the eminent physicist Georg Christoph Lichtenberg written in September 1784, Müller proposed building a more advanced machine for automatically calculating and printing tables of values of an arithmetical function. Müller further developed this idea in a 50-page pamphlet published two years later in which he refers to the method of finite differences, however, details were sketchy and the machine was never built.

Babbage named his new invention the Difference Engine. In order to test his ideas, he began by constructing a working model which was designed to calculate values of the formula $x^2 + x + 41$ to six decimal places using two orders of difference. The machine would have to be able to store columns of numbers, perform addition on them and execute a tens carry where necessary. He initially considered using sliding metal rods to represent the numbers but soon realised that the rotary motion of gearwheels provided a more natural method of resetting to zero following a carry operation and settled on a geared mechanism instead.

Babbage occasionally dabbled in mechanics and had set up a small engineering workshop in a room of his London home which he used to build the model. However, he lacked the specialist skills necessary to manufacture the more complex components, such as the gearwheels, so he employed various tradesmen on a contract basis for these parts. The model was completed in May 1822. The following month he demonstrated it to the Astronomical Society.

In July 1822, having established proof of principle, Babbage wrote an open letter to the President of the Royal Society, Sir Humphry Davy, proposing the construction of a full-scale machine that could be used for calculating astronomical, nautical and other numerical tables and which would automatically print the results. Babbage's letter reached the attention of the British government in April 1823 and was referred back to the Royal Society for advice. The Society's response was resoundingly positive and was bolstered by the Astronomical Society of London which awarded Babbage a gold medal for his proposal. These glowing endorsements helped to secure Babbage a meeting with the Chancellor of the Exchequer in June to discuss the possibility of government funding for the project. The Chancellor was clearly impressed by what he heard and promised Babbage the initial sum of £1,000, with an invitation to apply for further government funding at a later stage to cover the remainder of the estimated £5,000 cost of construction. When the grant was received in August 1823, it was for a more generous sum of £1,500.

In preparation for the construction of the Difference Engine, Babbage embarked on a short tour around Britain, visiting workshops and factories in order to

familiarise himself with the latest manufacturing techniques and ascertain the accuracy that could be achieved with each. This was to be the first of a number of such surveys conducted at various intervals over the next few years and the information gathered would prove very useful. However, lacking the practical engineering experience necessary to produce the engineering drawings for the Difference Engine himself and to cope with every element of its construction, Babbage had also hoped to find an engineer that he could work with to help realise his ideas and the tour was a failure in this respect. He then turned for advice to the civil engineer Marc Isambard Brunel, also a Fellow of the Royal Society, who recommended the toolmaker and draughtsman Joseph Clement.

Joseph Clement had an impeccable pedigree, having worked as chief draughtsman for two of the giants of mechanical engineering, the inventor Joseph Bramah and the machine tool pioneer Henry Maudslay. He left Maudslay's employment in 1817 to set up a small engineering workshop of his own at Southwark in southwest London, specialising in work requiring high accuracy. Clement was also a talented machine tool designer in his own right and he would later be awarded a gold medal from the Society for the Encouragement of Arts, Manufactures, and Commerce for a new type of facing lathe.

Babbage and Clement commenced work on the Difference Engine in the autumn of 1823. Babbage's specification called for a machine which could tabulate values of a polynomial to 16 decimal places using up to 4 orders of difference. The design that evolved featured sets of what Babbage called 'figure wheels', a combination of a gearwheel and a cylinder with numbers inscribed on its circumference, to represent each decimal digit. These were stacked in vertical columns, with one column for each order of difference plus an additional column at one end of the machine to store the resulting tabular values. Sandwiched between each figure wheel was an adding mechanism that employed a plunger and cam arrangement to couple an intermediary gearwheel to the figure wheel for the fraction of a revolution that corresponded to the number to be added. Intermediary gearwheels were designed so that they meshed with the corresponding figure wheel in the adjacent column, thus transferring the number to be added to the appropriate digit position in that column. Also located between figure wheels in each column was an elaborate carry mechanism which operated in conjunction with levers mounted on a row of vertical shafts positioned behind the figure wheel columns.

To reduce the mechanical strain on the machine's components when performing a large number of addition and carry operations simultaneously, operations were executed in four separate stages. This was achieved by splitting addition into two stages, one using the odd difference columns and the other using the even, each followed by a separate carry operation. An additional benefit of this scheme was that it reduced all calculations to four steps irrespective of the number of differences involved.

Implementation of the four stage calculation cycle necessitated the development of a sophisticated control mechanism to regulate the timing of the plungers for the intermediary gearwheels and control the overall sequence of operation. This was achieved using a device known as a 'barrel' which replicated the action of a set of cams whose profiles could be altered. It comprised a vertically mounted cylinder drilled with sets of holes in vertical rows spaced at regular angular intervals around its circumference, each of which could be fitted with a removable stud. The cylinder was rotated incrementally then pushed forward so that each stud position was presented in turn to a set of rods which controlled the action of the various parts of the machine. The sequence of operation could be altered by simply changing the positions of the studs. It seems likely that Babbage was inspired by a similar mechanism found in music boxes, where a revolving cylinder fitted with pins is used to pluck the teeth of a comb of tuned metal strips in the correct sequence.

The control mechanism of the Difference Engine also incorporated the apparatus for automatically printing the results. Babbage had conducted a study of printing machinery and initially planned to use moveable type which would be selected one piece at a time by the Engine and automatically assembled into blocks for printing. This was later changed to a system that punched numbers one digit at a time into a soft metal plate which would then be used as a mould for casting stereotype printing plates. A mechanism was designed to sense the final values at each digit position on the results column and select the corresponding digit on a punch mechanism. Another mechanism was provided to shift the plate along or down as required between each punch action. In this way, a complete page of tables could be built up automatically and it would only be necessary to add the headings and other annotations manually before printing. Provision was also made for altering the layout of tables by changing the settings on the pair of wheels that controlled the spacing of numbers.

In 1827, Babbage suffered a series of personal tragedies. The first of these was the death of his father in February, a not entirely unexpected event, given his father's advanced age and declining health, and one that also left Babbage a rich man. However, it was rapidly followed by the sudden death of his second son Charles in July and his beloved wife and newborn baby the following month. These events affected Babbage deeply and he was advised to take a long holiday for the sake of his health. After leaving Clement with instructions to continue work on the Difference Engine in his absence and requesting that John Herschel keep him informed of progress, Babbage embarked on an extended tour around Europe in October 1827, not returning until November 1828. This lengthy absence inevitably affected the project, which had now reached a critical stage, and progress slowed as a result.

With the initial government grant long spent, Babbage had been bankrolling the project with his own funds for some time. On his return from the continent,

he made it a priority to remind the government of its commitment to provide funding for the construction of the Difference Engine. Unfortunately, the absence of any written agreement made this difficult and he and his supporters had to lobby vigorously to force the government to act. After another referral to the Royal Society, Babbage succeeded in obtaining a government payment of £1,500 in April 1829 to reimburse his expenditure along with assurances that further funding would be forthcoming. However, work on the project came to an abrupt halt a few weeks later following an argument with Clement over the amount of money that Babbage owed him. Work only resumed after representatives of each party had been appointed to monitor the accounts but this had wasted a further 9 months.

Babbage had originally estimated that the Difference Engine would take 3 years to complete but the lack of funding, his prolonged absence abroad and the 9 month dispute with Clement had all put paid to this ambitious schedule. Finalisation of such a complex design also required considerable experimentation and the full set of engineering drawings was not completed until 1830. The final version incorporated two additional orders of difference and called for an estimated 25,000 individual parts. Designed on a relatively large scale with each figure wheel around 125 mm in diameter, the Difference Engine would have weighed several tonnes and stood over 2 metres high. Despite Babbage's earlier wish for calculations to be executed by steam, the machine was designed to be operated by hand.

With the drawings completed, the project now entered the construction phase. This too would be a time-consuming process given the enormous number of high precision components required. After two years, sufficient components were ready to assemble a sizeable section of the calculating mechanism. Babbage, mindful of the protracted timescale, wanted something that would provide the government with evidence of progress so he instructed Clement to build a demonstration piece comprising three columns from the calculating mechanism, each fitted with six figure wheels, along with sufficient ancillary components to allow the mechanism to be operated. The demonstration piece contained around 2,000 parts and was completed in December 1832. Although the control mechanism and printing apparatus were absent, Babbage was able to use this device to successfully calculate portions of a table of logarithms. It also formed the centrepiece of the frequent social gatherings that Babbage had become well known for hosting.

Final assembly of the Difference Engine would require a large dedicated space which Clement's workshop did not possess. Babbage had pressed for and succeeded in having the Engine declared government property two years earlier as part of the negotiations to secure further public funding. Concerned about security against fire and theft, he now persuaded the government to pay for the construction of a fireproof building in which to assemble and house the completed machine. Various sites were considered and rejected until Babbage,

who was growing weary of the daily 5 mile coach journey between his home in Marylebone and Clement's workshop in Southwark, insisted that the new building should be located on the site of some unused stables at his home. A small house adjacent which Babbage also owned would be made available for Clement to live in when he was on site. Clement was unhappy with these arrangements and demanded £660 per year as compensation for splitting his business between two locations, an exorbitant sum but one that seems to have reflected the deteriorating relationship between the two men. When this was refused in March 1833, Clement immediately halted construction and fired the ten workers that he had employed on the project. One of these was the engineer Joseph Whitworth, who would later use the knowledge he had gained working on the Difference Engine project to revolutionise standards of accuracy in engineering manufacture.

Clement's actions sounded the death knell for the beleaguered Difference Engine project. Although the majority of the components for the calculating mechanism had been manufactured, these still required to be assembled, a process that would have required considerable hand fitting of parts, and work had not yet started on the control mechanism and printing apparatus. Babbage drew up a list of possible options for the future of the project for consideration by the government. His preferred option was to complete the machine using an alternative engineering partner but Clement refused to release the drawings or the finished parts until he had received payment due for work already done. Several months went by before the Treasury agreed to pay Clement directly for the money he was owed and it would be more than a year before all the items, including the demonstration piece, were safely relocated to the new building next to Babbage's home. Clement was allowed to keep the special-purpose machine tools which he had developed for the construction of the Engine. Despite the loss of his most important customer in highly controversial circumstances, Clement's reputation seems to have remained intact and his business continued to thrive.

The total amount of government expenditure on the Difference Engine project came to £17,479 including the additional £2,190 spent on the fireproof building. This was a huge sum in an age where an entire steam locomotive cost less than £800. Moreover, Babbage estimated that a similar amount would be necessary to complete the machine. He continued to press for a decision from the government on the future of the project but a general election and political reforms delayed this for some years. When the decision finally came in November 1842, it was that no further government support would be forthcoming. Twenty one years after it had begun, the Difference Engine project was finally dead. Fortunately, Babbage had not been idle while awaiting the decision and was already several years into his next calculating machine project.

The Analytical Engine

The Difference Engine was by far the most technologically advanced calculating machine yet devised. However, as a special-purpose calculator for tabulating the values of a polynomial, it would have had limited applicability and it is perhaps more impressive as a feat of precision engineering than a calculating machine. Babbage's second major design project would be much more ambitious than the Difference Engine in this respect. It would be a general-purpose calculating machine which could be configured to automatically evaluate almost any mathematical expression.

Having recovered the drawings of the Difference Engine from Joseph Clement in July 1834, Babbage began to consider how to improve its operation. He had learned a great deal in designing the Engine's control mechanism and printing apparatus and he now set out to apply this knowledge to the development of new mechanisms that would extend its capability. Babbage had been aware for some time that the Difference Engine would be far more flexible if it was able to store intermediate results and feed them into subsequent calculations. He realised that this should be possible if the figure wheel columns were arranged in a circle so that the values appearing on the results column could be fed back into the highest order difference column. However, the tabulation of certain mathematical functions also required the ability to perform multiplication as well as addition and this could only be achieved by separating out the calculating functionality from the storage of numbers. The figure wheel columns would then become a collection of independently addressable numerical storage units which Babbage called the 'store'. A separate part called the 'mill' would contain the circular calculating mechanism which could be connected through linkages with any column in the store to produce the desired result. These two architectural elements would form the basis of what came to be known as the Analytical Engine.

Fired up by the potential of this new architectural configuration, Babbage set to work on the functional design. He began by designing a mechanism which could perform multiplication using essentially the same method of repeated addition employed by Leibniz in his Stepped Reckoner of 1674. Single digit multiplicands would be dealt with by repeatedly adding the operand to itself, with the number of repeat operations dictated by the value of the multiplicand. For multiplicands with more than one digit, this sequence would be repeated for each additional digit and the column digits shifted up by one place each time to correspond with the position of the digit in the multiplicand.

Babbage also designed an automatic division mechanism for the Analytical Engine which would operate by a process of repeated subtraction and stepping in a similar manner to the method of multiplication. An elaborate mechanism would compare the divisor with the remainder after each subtraction operation to determine whether a further subtraction operation should be performed or

the decimal place shifted.

The sequence of operation of the Analytical Engine involved transferring numbers from the store to the mill, performing arithmetical operations on them and transferring the results back to the store. The process of fetching a number from the store entailed rotating each of the figure wheels in that column to the zero position while a geared mechanism, operating in a similar fashion to the adding mechanism in the Difference Engine, transferred this movement to the mill via a rack and pinion arrangement. However, because numbers would be erased during this process through the action of resetting to zero, those that required to be retained for later use would have to be copied back to the store. This could be achieved by simply leaving the rack and pinion gearing engaged when restoring it to its starting position following a transfer.

The introduction of multiplication and division would place additional demands on the tens carry mechanism. This had been designed to operate sequentially in the Difference Engine, making multiple carries propagated across several digit positions a lengthy process. As Babbage intended to use much larger numbers of 40 digits or more in the Analytical Engine, a method had to be found for speeding up the process of propagating a multiple carry across such a large number of digit positions. Babbage solved this by inventing an anticipating carry mechanism, designing and testing more than twenty different versions before arriving at the optimum configuration. Each figure wheel was fitted with an arm which incorporated a circular end with a vertical hole drilled through it. When the wheel rotated to the 9 position, a rod located beneath was able to pass through the hole in the arm, allowing a sector gear attached to be lifted into mesh with the figure wheel above. This mechanism was carefully designed so that the movement of the rod would propagate through each digit position, thereby setting the sector gear to mesh at each position where the arm was in the correct alignment for a carry. When the lowermost figure wheel was rotated from the 9 to the 0 position, the sector gear would transmit this movement to a common shaft which rotated every other sector gear in that column. In this way, each figure wheel in a column that required to be changed as a result of a carry would be rotated simultaneously.

The expanded functionality of the Analytical Engine demanded a highly sophisticated control mechanism that could not only handle the numerous individual steps involved in a multiplication or division calculation but would also cope with the complex interconnections between the store and the mill and would allow changes to the overall sequence of operation to be made for different mathematical expressions. To provide this, Babbage extended the control barrel concept that he had developed for the Difference Engine. Individual barrels with fixed studs were employed to control the operation of each calculating mechanism while a central barrel with removable studs was provided to direct the overall sequence of operation.

Babbage devoted considerable time and effort to the functional design of the Analytical Engine over the next year or so and by November 1835 he had made sufficient progress to begin the detailed engineering design. He hired an experienced draughtsman, Charles G Jarvis, to oversee the production of the engineering drawings and two assistants to help him. Jarvis was perfectly suited to the task, having served as senior draughtsman on the Difference Engine project before losing his job when Clement halted construction.

Engineering drawings provide all the information necessary to manufacture the parts for a machine and permit it to be assembled correctly but they do not describe its operation. Babbage had first encountered this limitation when designing the Difference Engine some years earlier and had created a form of mechanical notation to describe the movement of parts and how they interact. This consisted of a system of symbols to indicate the source and type of motion and whether the mechanical connection between components was permanent, such as when they are attached to a common shaft, as a result of friction between them or imparted through an intermittent arrangement such as a cam or ratchet. These symbols were incorporated into a table which provided information on the sequence and timing of operations. In this way, it would have been possible to determine the position of any component at any point during the cycle of operation of the machine. Babbage had published a description of his mechanical notation in the Philosophical Transactions of the Royal Society in 1826. He now found it an invaluable tool in designing the intricate mechanisms of the Analytical Engine.

As the design of the Analytical Engine progressed, Babbage turned his attention to how the machine would be used. Through attempting to produce sets of control sequences for the machine, Babbage realised that he needed greater flexibility in the control mechanism. He found an ideal solution in the punched card technology that had been developed in France to control weaving looms. The technology had been introduced in 1801 by a French silk weaver, Joseph Marie Jacquard, based on earlier work by the inventor Jacques de Vaucanson. Jacquard's loom was controlled by pasteboard cards with holes punched into them, each row of which corresponded to one row of thread in the pattern. The presence or absence of a hole dictated the position of a hook which controlled how the fabric was woven by raising or lowering a longitudinal thread. Highly intricate patterns could be produced by stringing together sets of cards in a particular order. Furthermore, the number of cards in a set was not limited, unlike Babbage's control barrels which were restricted to a specific number of steps before the barrel came full circle and the sequence repeated.

Babbage began to incorporate punched card technology into the design of the Analytical Engine in June 1836. He designed a card reading mechanism which sensed the presence or absence of holes by presenting each card in turn to a set of levers located at each hole position. Levers would be unobstructed by the card if a hole was encountered or pushed backwards if there was no hole at that

position. The levers were attached to a mechanism that converted their final positions into the appropriate action. Barrels were retained to control the low-level sequence of operations while the punched card mechanism controlled the positioning of the central barrel which now had fixed studs.

Punched cards were also used to input numbers into the Analytical Engine, thus reducing the possibility of operator error when setting numbers manually, and to specify which locations in the store were to be used. These were known as 'variable' cards to differentiate them from the 'operation' cards that directed the calculation functions of the machine. As they differed in size and number of hole positions from the operation cards, a separate card reading mechanism was provided to accommodate them.

Babbage's card readers also possessed the ability to skip forward or backward by a specified number of cards when a particular condition had been met during a calculation, such as a change of sign or a predetermined counter value having been reached. Known in modern computing terminology as a conditional branch, this powerful feature would permit control to be switched to different sections of the card set in order to ignore operations which were no longer required by a calculation or to create loops of repeated operation sequences.

For the output of results, the Analytical Engine would incorporate an improved version of the stereotype printing plate apparatus devised for the Difference Engine but it also included provision for printing results directly onto paper or recording them onto punched cards by means of a card punching mechanism. This latter feature also extended the machine's ability to store intermediate results.

The design of the Analytical Engine was essentially complete by 1838 but Babbage continued to refine it for a further nine years, finally ceasing work in 1847. Much of this later work was aimed at simplifying the design and reducing the number of components but he also took the opportunity to redesign the multiplication and division mechanisms to speed up calculation. This was achieved through the implementation of the method of partial products, where a table of the nine single-digit multiples of the multiplicand or divisor is first calculated then added together or subtracted as dictated by the value of the multiplier or dividend. Adopting this method would allow operations to be overlapped, thereby reducing the time required to perform a multiplication operation to around 1 minute for two 40-digit numbers. Dedicated columns of figure wheels in the mill provided the required storage for the table of multiples.

Babbage paid for the design work out of his own pocket but he never sought reimbursement for this expenditure or attempted to raise the additional funding necessary to construct the Analytical Engine. There are hints that he was hoping the government would approach him but this would have been highly unlikely, given Babbage's poor track record on the Difference

Engine project and a less obvious need for a machine with the Analytical Engine's capabilities. Government apathy towards the project also prompted Babbage to decline a generous offer of technical and financial assistance from Joseph Whitworth, who was now a successful engineering manufacturer. Consequently, the only parts of the Analytical Engine which were built were a few mechanical assemblies and test models relating to the mill and the anticipating carry mechanism, although Babbage later experimented with the newly introduced die casting process as a means of manufacturing gearwheels more economically.

The completed Engine would have stood over 4 metres high. Its length would have been dictated by the size of the store, which projected out in a line from the side of the mill. Babbage wrote of the store having a capacity of 1,000 numbers but this would have been unrealistic and 100 numbers would have been sufficient for most calculations, giving an overall length of around 4 metres. Requiring more power to operate than the Difference Engine, the machine would indeed have been driven by a small steam engine.

A Second Difference Engine

In 1846, having almost completed his revisions to the design of the Analytical Engine, Babbage turned his attention back to his earlier machine. Using the knowledge he had gained in the design of the Analytical Engine, Babbage undertook a complete redesign of the Difference Engine, simplifying the calculating mechanism and reducing the number of components. This became known as the Difference Engine No. 2.

The general architectural design of the Difference Engine No. 2 was unaltered from his earlier machine but Babbage took the opportunity to upgrade the specification by increasing the numerical precision from 17 to 31 decimal digits and raising the number of orders of difference from 6 to 7. Despite the higher specification, Babbage was able to dramatically reduce the component count from 25,000 to around 8,000. This was achieved by adopting the simpler addition and carry mechanisms developed for the Analytical Engine. The Difference Engine No. 2 also shared the same stereotyping and printing mechanism as the Analytical Engine.

A full set of engineering drawings for the Difference Engine No. 2 was completed by 1849 under the supervision of Charles Jarvis. At the suggestion of the President of the Royal Society, Babbage offered the design to the British government. He wrote to the Prime Minister Lord Derby in June 1852 offering to donate the drawings and notations for the machine as a gift to the nation on condition that it would be built. Letters of support were also submitted by various interested parties, including the inventor and machine tool manufacturer James Nasmyth, who highlighted the considerable advances in machine tool technology made during the first Difference Engine project and

the resulting benefits to industry. The matter was referred to the Chancellor of the Exchequer, Benjamin Disraeli, who seems to have allowed his distaste of all things scientific and technological to cloud his judgement. Ignoring expert advice, Disraeli decided that the project would be too expensive and rejected Babbage's offer.

The following year, the Swedish inventor Georg Scheutz and his son, Edvard, succeeded where Babbage had twice failed by completing the construction of their own difference machine. Scheutz had been inspired by an article on Babbage's first Difference Engine which appeared in the July 1834 issue of the Edinburgh Review magazine. Assisted by his engineering student son, Scheutz began work on the machine in 1837 and a working model was completed by 1840 but full-scale construction was only possible following a grant from the Swedish government in 1851. The specification of the Scheutz machine was similar to Babbage's original, with 15 decimal digits and 4 orders of difference. However, it was built on a far smaller scale and differed considerably in the detail of its design and in its method of operation.

Following completion in October 1853, the Scheutz difference machine was brought to London where it received considerable attention. It was examined by a committee appointed by the Royal Society, which acknowledged the machine's potential for recalculating and printing existing numerical tables in order to weed out errors. The machine was then exhibited at the Paris Exposition of 1855, where it was awarded a gold medal in a category that included Thomas de Colmar's Arithmometer. To the great surprise of many who knew him, Babbage welcomed this new development. He befriended the Scheutzs and became an enthusiastic supporter of their work but he also seized every opportunity to remind anyone who would listen that it was he who had first conceived such a device.

After the Paris Exposition, the Scheutz machine was loaned to the Paris Observatory while a buyer was sought. With Babbage's help, it was sold in December 1856 to the Dudley Observatory in Albany, New York, for £1,000. The following year a copy was commissioned by the British General Register Office to assist in the calculation of life expectancy tables. This was built by the firm of Bryan Donkin & Company, a British printing machine manufacturer which had been instrumental in bringing the original Scheutz machine to London. The new machine was delivered in July 1859 but was found to be unreliable in use despite incorporating several improvements over the original Scheutz design.

Babbage's Legacy

Though always a somewhat eccentric character with an obsessive nature, Babbage became more irascible with age and his later years were marked by a bizarre campaign against street musicians, particularly organ grinders.

These efforts resulted in the passing of an Act of Parliament in July 1864 which outlawed such activities in central London but the new law was not welcomed by the general public. Instead, Babbage was ridiculed in the press and became a target for harassment by every street musician in London. He increasingly withdrew from the London social scene in which he had been such an active participant for much of his life and his final years were spent in relative isolation. Babbage died at the age of 79 in October 1871, only five months after his lifelong friend John Herschel.

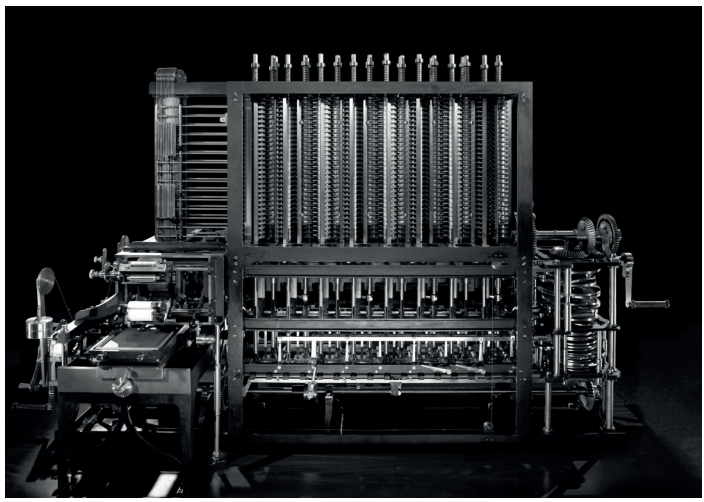
Although he had failed to realise either of his two great inventions, Babbage achieved much throughout a long and highly productive life. He was active in several other fields, including cryptography, where he broke the Vigenère cipher, a powerful encryption method which was thought to be unbreakable. He also dabbled in politics, standing unsuccessfully as Liberal candidate for the London borough of Finsbury in the General Election of November 1832 and again in June 1834 when the seat became vacant. An influential book, 'On the Economy of Machinery and Manufactures', which was first published in 1832, was the result of Babbage's lengthy studies of manufacturing techniques. There is also no question that his ten-year collaboration with Joseph Clement advanced the art of precision engineering enormously, a fact borne out by the esteem in which Babbage was held by the eminent engineers Joseph Whitworth and James Nasmyth. His abilities as a mathematician were also recognised by his appointment as Lucasian Professor of Mathematics at Cambridge University from 1828 to 1839, a position once held by no less a figure than Sir Isaac Newton.

After Babbage's death his youngest surviving son, Henry P Babbage, completed several fragments of his father's Engines, including a number of small demonstration pieces assembled from unused parts of the Difference Engine No. 1. Henry also campaigned for the Analytical Engine to be built. However, in 1878 a committee appointed by the British Association for the Advancement of Science concluded that the complexity of the design and insufficient detail in the drawings made it impossible to be certain that the machine would operate as planned if constructed. Instead, they suggested that a simpler machine might be built using selected parts of the mechanism. This prompted Henry to construct a section of the mill of the Analytical Engine which he cleverly reconfigured to operate as a four function calculator. Following completion in 1906, Henry used this machine to successfully calculate multiples of Pi.

In 1985, the Science Museum in London initiated a project to construct a full-scale replica of Babbage's later design for his first machine, the Difference Engine No. 2. Certain assumptions had to be made, however, as the original drawings lacked information on the choice of materials, machining methods, manufacturing precision and finishes. Nevertheless, Babbage's design was followed faithfully and only two corrections were necessary to render the mechanism operational. With the help of a local engineering design firm and

various specialist subcontractors, the calculating mechanism was completed by November 1991, in time for an exhibition commemorating the bicentennial year of Babbage's birth. Although modern machine tools were employed to produce the components for the Engine, the quality of manufacture was strictly limited so that it remained within the standards of engineering precision achievable when Babbage designed it.

Further funding to enable the construction of the stereotyping and printing mechanism for the machine was provided by Nathan Myhrvold, a senior executive with the US software giant Microsoft. This was completed and added to the calculating mechanism in March 2002. The whole machine contains over 8,000 parts and weighs 5 tonnes. Myhrvold also provided additional funding for a second replica to be built for his private collection. This was completed in 2009 and is currently on loan to the Computer History Museum in Mountain View, California. The fact that these replicas exist and operate according to specification is vindication of Babbage's reputation and proof that the engineering technology available to him in the 1840s was indeed capable of producing working versions.



Replica of Babbage's Difference Engine No. 2 (Photo © Copyright xRez Studio)

Babbage's greatest legacy is the Analytical Engine. He left approximately 300 engineering drawings and more than 600 notations and 6,000 pages of notebooks describing the Engine and its components. These are now in the collections of the Science Museum. However, Babbage never provided a detailed description of the operation of the Analytical Engine nor discussed his ideas for its use in any detail and this has hampered our understanding of it. Fortunately, we have the valuable contribution of Augusta Ada Gordon, later Ada King, Countess of Lovelace.

The daughter of the infamous Romantic poet Lord Byron, Ada Lovelace showed an early aptitude for mathematics. She first met Babbage as a teenager in 1833 and was captivated by his description of the Difference Engine. Babbage became her mentor, offering advice on her mathematical studies and introducing her into his circle of intellectual friends. In August 1840, Babbage attended a scientific meeting held in the Italian city of Turin at which he gave a series of presentation on the Analytical Engine. Among the attendees was the Italian military engineer and mathematician Luigi Federico Menabrea. Menabrea was so impressed by Babbage's work that he wrote an article describing the Engine which was published in a Swiss journal in October 1842. In an effort to generate some positive publicity for Babbage in the wake of the November 1842 decision to withdraw government support for the Difference Engine project, Ada translated Menabrea's article from French into English and submitted it for publication in a British journal. She also added copious notes which were prepared in consultation with Babbage.

Ada Lovelace's notes on the Analytical Engine choose to ignore the engineering details of the mechanism and focus instead on how the machine would be used to solve mathematical equations. They show that her understanding of the limitations and the capabilities of the Engine went deeper than Babbage's. In them, she discusses the possibility of referring to storage locations numerically and of using the machine to manipulate symbols, two important concepts that predate their rediscovery by the pioneers of digital computers by almost a century, and there is little doubt that she would have played a pivotal role in putting the machine to work had the Analytical Engine been built.

With the potential to perform complex mathematical calculations automatically, the Analytical Engine was the first true general-purpose computing device and its development has rightly been called one of the great intellectual achievements of humankind. However, despite a striking similarity between the functional design of the Analytical Engine and the architecture of today's electronic digital computers, there is no direct evolutionary link between the two. Babbage's failure to complete any of his Engines and the dearth of written material on the operation of the Analytical Engine meant that his astonishing achievements went largely unrecognised for many years and only fully came to light after the pioneers of digital computers had reinvented much of his work. We can only wonder as to how much further ahead progress in computer technology would have been, and the different path that it might have taken, had Babbage actually succeeded in constructing this incredible machine.

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